Title

Performance Assessment for the Area 5 Radioactive Waste Management Site at the

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NTS EIS
ADMINISTRATIVE RECORD

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PERFORMANCE ASSESSMENT FOR THE AREA 5 RADIOACTIVE WASTE MANAGEMENT SITE AT THE NEVADA TEST SITE, NYE COUNTY, NEVADA

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EXECUTIVE SUMMARY

This report documents the methodology and results of a performance assessment conducted for the Area 5 Radioactive Waste Management Site (RWMS) at the Nevada Test Site (NTS). The United States Department of Energy (USDOE) has established policies and guidelines for the disposal of radioactive waste in USDOE Order 5820.2A (USDOE, 1988a), which requires each disposal site to prepare and maintain a site-specific performance assessment. A performance assessment is a systematic analysis of the potential risks posed by waste management systems to the public and to the environment, and the comparison of those risks

FACILITY DESCRIPTION

The NTS is a USDOE-operated facility occupying 3,500 km^2 of arid Basin and Range topography in southern Nye County, Nevada. The NTS was used as the continental nuclear weapons testing site from 1951 to 1992. The Area 5 RWMS is located within Frenchman Flat, a closed alluvium-filled basin in the southeastern corner of the NTS. The closest permanent settlement to the RWMS is Indian Springs, 42 km to the southeast.

In 1961, the Area 5 RWMS began disposal of low-level radioactive waste generated at the NTS. The RWMS began accepting waste from offsite USDOE generators for disposal in 1978. From 1983 to 1989, high-specific activity waste was disposed of in deep augered shafts known as Greater Confinement Disposal (GCD). Mixed waste was disposed of in a single unlined pit from 1987 to 1990. Since the inception of USDOE Order 5820.2A in 1988, the Area 5 RWMS has disposed of low-level waste and mixed waste in shallow unlined trenches and pits. A single GCD borehole has received waste since 1988. The Area 5 RWMS is currently receiving low-level wastes from the NTS and offsite USDOE generators. This performance assessment is limited to wastes disposed from the inception of USDOE Order 5820.2A to the estimated date of closure.

The Area 5 RWMS lies within a region transitional between the Mohave Desert and the Great Basin Desert. The climate is characterized by many cloudless days each year, low precipitation and high daily temperatures. Frenchman Flat receives an average annual precipitation of approximately 12 cm. Potential evapotranspiration greatly exceeds precipitation.

The stratigraphy beneath the RWMS can be classified into eight primary units. These units are composed of clastic rocks and carbonate rock in the bottom sections, and volcanic rocks and alluvium in the upper sections. The RWMS lies directly upon approximately 360 to 460 m of alluvium derived predominately from the Tertiary volcanic rocks exposed in the nearby mountain ranges. Beneath the alluvium lies a layer of interbedded ash-flow tuff, estimated to be over 550 m thick, and an undetermined thickness of carbonates, which extend down to the Precambrian basement rocks.

The surface hydrology at the NTS is characterized by ephemeral runoff occurring after infrequent storm events. The sub-surface hydrology is characterized by a deep groundwater regime overlain by a very thick unsaturated zone. The saturated zone beneath the RWMS lies within the valley fill alluvium, about 240 m below the surface. The water table is essentially flat, indicating that there is no significant horizontal flow beneath the RWMS in the saturated zone.

The alluvium within the unsaturated zone is very dry, having a volumetric water content of approximately 12 percent at depth. The dry conditions are the result of evapotranspiration greatly exceeding precipitation. Chloride and stable isotope analyses indicate that infiltration is very rare. Indeed, the evaporative demand is so high at the surface that the tendency for liquid flow in the top 35 m of alluvium is toward the surface, rather than downward to the aquifer. Thus, leachate from the waste is extremely unlikely to contaminate the uppermost aquifer beneath the RWMS. Below 35 m in the vadose zone, liquid will tend to move downward at extremely slow rates. In the unlikely event that leachate were to move below 35 m, it was estimated that it would take approximately 65,000 years for the liquid to reach the water table under the current hydrologic regime. Retardation due to sorption reactions would greatly increase this transport time for most radionuclides.

The alluvium above the waste disposal cells is normally near its residual water content of approximately 8 percent. Radionuclide transport by upward advection or upward diffusion is provide a reasonable, yet conservative, estimate of the performance of the undisturbed site. Intruder scenarios are hypothetical events evaluated to set conservative waste concentration limits.

Release and Pathway Scenarios for the General Public

Two exposure scenarios for the general public were developed based on current land use patterns in southern Nevada. The first scenario, the transient occupancy scenario, assumes that members of the general public visit the site for recreational or commercial activities, but do not permanently reside near the site. The second scenario, the open rangeland scenario, assumes that a ranch has been established at the nearest available site with water and that range fed cattle have access to the closed disposal site.

The dose to the general public under the assumptions of the transient occupancy scenario was estimated for a screened list of non-volatile radionuclides at 100 years, 10,000 years, and at the time of the maximum dose. In the first 10,000 years after closure, the total effective dose equivalent (TEDE) from all non-volatile radionuclides would be less than 1 mrem yr^{-1} to a person spending up to 2,000 hours per year at the Area 5 RWMS. The dose is mostly due to external exposure from the short-lived progeny of ^{226}Ra and inhalation of ^{238}U. Since estimated doses are linear in time of occupancy, it is possible to estimate the dose per hour spent at the site. Individuals visiting the site 10,000 years after closure are expected to receive a TEDE of approximately 3×10^{-4} mrem for each hour spent at the site.

The release of volatile radionuclides was evaluated separately. These calculations were done under the extremely conservative assumption that gaseous radionuclides were released at a maximum rate, based on diffusion in the air-filled pores and diluted into a 2 m atmospheric mixing zone. The TEDE from ^{3}H, ^{14}C, and ^{85}Kr combined was less than 0.01 mrem yr^{-1} at 100 years.

Doses were evaluated under the assumptions of the open rangeland scenario for two offsite locations with water resources, Indian Springs and Cane Springs. The maximum TEDE within the 10,000-year compliance interval was less than 0.2 mrem yr^{-1} and occurred at 10,000 years. The doses at the two offsite locations are approximately equal because most of the dose is attributable to ingestion of beef and milk produced at the Area 5 RWMS. Approximately 85 percent of the dose at 10,000 years is attributable to the ingestion of ^{238}U, ^{234}U, and ^{210}Pb and its short-lived progeny in milk.

Volatile radionuclides were again evaluated separately. Volatile radionuclides were assumed to be released from the site by diffusion and advected through the atmosphere to the offsite location. Due to the great dilution, the TEDE is much smaller than 0.001 mrem yr^{-1}.

The radon flux was estimated for two inventories, the average inventory disposed of by shallow land burial and the estimated inventory for Pit 6. Pit 6 is expected to receive thorium wastes that have the potential to generate ^{222}Rn as ^{230}Th decays. The thorium is destined for a deeper or lower cell. Routine low-level waste (LLW) will be disposed of in the upper cell.

The flux of ^{222}Rn released from the disposal site was assumed to be directly proportional to the activity concentration of ^{226}Ra in the buried wastes. For the shallow land burial inventory, the activity concentration of ^{226}Ra will increase very slowly over the next 10,000 years, not reaching a peak for several million years. The predicted flux remains below the performance objective of 20 pCi m^{-2} s^{-1} throughout the 10,000-year compliance interval. The flux exceeds the performance objective in approximately 30,000 years and reaches a peak of 156 pCi m^{-2} s^{-1} in 3.5×10^6 years.

The performance assessment results in Table 1 provide reasonable assurance of compliance with the performance objectives for members of the general public. The two scenarios considered, the transient occupancy scenario and the open rangeland scenario, could involve exposure of the same individuals. The TEDE for the two scenarios combined is less than 1 mrem yr^{-1}, well below the 25 mrem yr^{-1} performance objective.

Intruder Scenarios

Intruder scenarios are hypothetical events analyzed to set activity concentration limits for wastes suitable for disposal in the near surface. Three intruder analyses, one acute and two

scenario (chronic), and post-drilling scenario (chronic).

The drilling scenario is a short-term exposure scenario, where an intruder is exposed to contaminated drill cuttings while drilling a water well at the site. An inadvertent intruder drilling through a shallow land burial trench or pit is estimated to receive a TEDE of

The intruder post-drilling scenario assumes that an intruder builds a residence on an area contaminated with drill cuttings from the disposal site. As in the intruder-agriculture scenario, the intruder produces meat, milk, fruit, and vegetables within the contaminated zone.

The estimated TEDE at 100 years was 0.70 mrem yr^{-1} for a post-drilling intruder penetrating a shallow land burial trench. At 10,000 years the dose increases to 0.71 mrem yr^{-1}, again due to external irradiation from ^{226}Ra and its short-lived progeny.

A single pit (Pit 6) has been modified to accept a thorium waste stream. The pit has been excavated to a greater depth to allow burial of the thorium waste in a deeper or lower cell. The greater depth of burial was required to attenuate radon fluxes and reduce the potential for intrusion. However, since the depth of burial does not eliminate the potential for drilling intrusion, the estimated Pit 6 inventory was analyzed in the post-drilling scenario as a special case. The estimated TEDE at 100 years was 163 mrem yr^{-1}. The thorium waste in the lower cell contributes 99 percent of the dose. By 10,000 years, the TEDE is predicted to increase to 178 mrem yr^{-1}, due to external irradiation from ^{226}Ra and its short-lived progeny produced by the radioactive decay of ^{230}Th.

The inventory assumed for Pit 6 was found to exceed the performance objective when analyzed in the post-drilling scenario. The analysis did not meet the performance objective because of the concentration of ^{232}Th assumed for the lower cell. This analysis used an estimated inventory based on the average concentration of wastes already received. A thorium inventory of 174 Ci for Pit 6 will assure compliance with the performance objective. Since only 18 Ci have been received to date, imposition of an inventory limit for Pit 6 can assure compliance. The results of intruder scenario analyses are presented in Table 2.

Table 2. Performance assessment results for intruder scenarios. Results are based on current waste management practices or assumed inventories.

Performance Objective	Performance Assessment Result	
	Shallow Land Burial	Pit 6 (PO6U)
Acute Scenario: 500 mrem Drilling	0.2 mrem	23 mrem
Chronic Scenario: 100 mrem yr^{-1} Agriculture Post-Drilling	 157 mrem yr^{-1} 0.7 mrem yr^{-1}	 NA 178 mrem yr^{-1}

NA - Scenario not applicable

The results in Table 2 indicate that there is currently reasonable assurance of compliance with the performance objectives for intruders, except for the intruder-agriculture scenario and for the post-drilling scenario analyzed for the inventory assumed for Pit 6. Reasonable assurance of compliance for the intruder-agricultural scenario can be obtained by requiring a final closure cap of at least 4 m. Compliance in the future can be assured by development of waste acceptance criteria based on performance assessment results. Implementation of an inventory for waste disposed in Pit 6 in the future can assure compliance with the post-drilling scenario for this waste disposal unit.

1.0 INTRODUCTION

The NTS is a USDOE-operated proving ground for defense-related technologies. It is located in the sparsely populated Mohave Desert of southern Nye County, Nevada. The southern boundary of the NTS is approximately 105 km northwest of Las Vegas.

Two permanent radioactive waste management sites have been established on the NTS. The Area 5 RWMS was established in 1961 for the disposal of LLW generated on the NTS. In 1978 the role of the Area 5 RWMS was expanded to include disposal of LLW from offsite USDOE generators and classified LLW from U.S. Government Agencies. The Area 3 RWMS was established in 1979 for the consolidation and disposal of atmospheric testing debris. The Area 3 RWMS currently accepts LLW in bulk containers from onsite and offsite generators. The two sites, approximately 27 km apart, are considered separate disposal sites for the purpose of performance assessment. This report is limited to the performance of the Area 5 RWMS.

1.1 PURPOSE AND SCOPE

This report's purpose is to document the methodology and results of a performance assessment conducted for the Area 5 RWMS. In USDOE Order 5820.2A (USDOE, 1988a), which requires that each disposal site prepare and maintain a site-specific performance assessment, the USDOE has established policies and guidelines for the disposal of radioactive waste. A

Performance assessments are intended to be living documents reviewed and revised as necessary. This assessment is based on the best information available at the time of preparation. Additional analyses may be required if significant changes occur in waste management practices, the disposal site inventory, or in the conceptual understanding of how the waste disposal system functions.

The scope of the performance assessment has been limited in four specific areas: the waste inventory, the time period for compliance assessment, waste types and constituents, and waste management practices. The scope has been limited to these areas based on the requirements and policies of USDOE Order 5820.2A and USDOE guidance on performance assessment (Case and Otis, 1988; Dodge et al. 1991; Wood et al. 1994).

The performance assessment considers wastes disposed in Area 5 from 1988, when current USDOE waste management orders were issued, to the estimated date of closure. The Area 5 RWMS began accepting wastes from offsite generators in 1978. Assuming a 50-year operational lifetime beginning in 1978, the closure date becomes 2028. Since the analysis has been limited to disposals occurring after 1988, the operational period evaluated becomes 40 years.

USDOE Order 5820.2A does not specify an explicit period for assessment of compliance. Existing federal regulations governing disposal of radioactive wastes have set compliance periods ranging from 1,000 to 10,000 years, depending on the waste type and transport pathway. This performance assessment evaluates compliance with the performance objectives for a period of 10,000 years. However, the performance of the undisturbed disposal site has been assessed for the period beginning with the start of the active institutional control period and ending when the maximum dose is predicted. In some instances, these analyses have been performed beyond 10,000 years. These analyses are provided to give the reader an indication of how doses are increasing or decreasing at the end of the 10,000-year compliance interval. Estimates of site performance at such great times in the future are highly uncertain. The time periods used in the analysis are defined in Table 1.1.

Table 1.1. Time periods for analysis.

Period	Duration	Date
Operational	40 years	1988 - 2028
Active Institutional Control	100 years	2029 - 2128
Post-Institutional Control	10,000 years	2129 - 12129

The performance assessment has been limited to radioactive and mixed wastes that have been permanently disposed of at Area 5 since the inception of USDOE Order 5820.2A on September 26, 1988, plus those expected to be received by the closure date. Wastes currently in storage, such as transuranic (TRU) wastes and the Mound Strategic Materials, have not been considered. In the past, wastes have been disposed of by shallow land burial in unlined pits and trenches, and by burial in deep 36 m augered shafts known as (GCD). This performance assessment considers wastes disposed of in both units.

Classes of wastes disposed in Area 5 include low-level radioactive wastes, mixed wastes, greater than Class C wastes, and TRU wastes. Only low-level radioactive and mixed wastes have been disposed of since 1988. Therefore, analyses have been limited to these two classes

Disposal of low-level radioactive wastes has occurred at two sites on the NTS, the Area 5 RWMS and the Area 3 RWMS. The Area 5 RWMS is located in Frenchman Flat, approximately 130 km northwest of Las Vegas. Since 1978, the Area 5 RWMS has served as a LLW disposal facility for the NTS and offsite USDOE and U.S. Department of Defense (USDOD) generators. Disposal activities are currently limited to a 37 ha site. An additional 259 ha are available for expansion.

Frenchman Flat is an alluvial-filled closed basin, typical of the Basin and Range province. The climate is extremely arid. Low precipitation, combined with high temperatures and low humidities, lead to high evaporation rates. Approximately 240 m of dry unconsolidated alluvial sediments from the surrounding mountain ranges lie between the site and the uppermost aquifer. Recent hydrogeologic characterization studies suggest that recharge through the alluvial sediments is not occurring under the current climatic conditions. The arid climate, low or non-existent recharge, and great distances to the water table make radionuclide transport through the vadose zone to the aquifer unlikely under the current climatic conditions.

Radionuclide transport through terrestrial and atmospheric pathways is insignificant under the current institutional controls because of the integrity of the disposal site and the remote location. The nearest offsite residents reside in Indian Springs, Nevada (Population 1,500), 42 km to the southeast. The arid climate, infertile soils, and lack of known mineral resources limit the potential future uses of the site. Land uses in the region include grazing, small scale irrigation-based agriculture, mining, and recreational activities. Frenchman Flat is not an attractive site for any of these uses under current economic conditions.

1.3 PERFORMANCE OBJECTIVES

LLW disposal performance objectives establish the limits of risk acceptable for the permanent disposal of radioactive wastes. A performance assessment must identify each performance objective and conduct the appropriate analyses to assess compliance with the objective.

Radiation protection standards and recommendations have used a variety of dosimetric quantities. The biological risks of exposure to ionizing radiation are believed or assumed to be proportional to the dosimetric quantity of dose equivalent or quantities derived from the dose equivalent (i.e., effective dose equivalent, committed dose equivalent, and committed effective dose equivalent). The International Commission on Radiological Protection (ICRP) has used the term "committed" to describe the dose equivalent and the effective dose equivalent received over a 50-year interval from a single year of intake. ICRP recommended limits for internal exposures use 50-year committed dosimetric quantities. Historically, some

U.S. Government regulatory agencies have used the quantities of dose equivalent and effective dose equivalent calculated for a single year. With the publication of the *USDOE Radiological Control Manual* (USDOE, 1992), the USDOE adopted the use of committed dosimetric quantities. Committed dosimetric quantities are always greater than or equal to annual doses and their use is always conservative, assuming the same dosimetric model is used. Since the use of committed doses is consistent with International Commission On Radiation Protection (ICRP) recommendations and the guidance in the *USDOE Radiological Control Manual*, all radiation standards used in this assessment will be assumed to be set in committed dosimetric quantities. The specific quantities used throughout this report are the committed effective dose equivalent (CEDE) and the (TEDE) as defined by USDOE (1992).

1.3.1 USDOE Order 5820.2A, Radioactive Waste Management

Performance objectives for the management of LLW are contained in USDOE Order 5820.2A. The performance objectives are:

1. Protect public health and safety in accordance with standards specified in applicable EH Orders and USDOE Orders.

2. Assure that external exposure to the waste and concentrations of radioactive material which may be released into surface water, groundwater, soil, plants, and animals result in an effective dose equivalent that does not exceed 25 mrem yr^{-1} to any member of the public. Releases to the atmosphere shall meet the requirements of 40 CFR 61. Reasonable effort shall be made to maintain releases of radioactivity in effluents to the general environment ALARA.

3. Assure that the committed effective dose equivalents received by individuals who inadvertently may intrude into the facility after the loss of institutional control (100 years) will not exceed 100 mrem yr^{-1} for continuous exposure or 500 mrem for a single acute exposure.

4. Protect groundwater resources consistent with federal, state, and local requirements.

The performance objectives above include additional standards. The first performance objective invokes other EH Orders and USDOE Orders applicable to the protection of public health and safety. USDOE Order 5400.5, *Radiation Protection of the Public and the Environment* (USDOE, 1990), is the principal USDOE radiation protection standard for the public. The second performance objective cites 40 CFR 61, the National Emission Standards for Hazardous Air Pollutants (NESHAP). The limits contained in the second performance objective are assumed to be a TEDE.

The third performance objective sets limits for inadvertent intruders, who are assumed to be individuals that enter the disposal site with no knowledge of its existence and expose buried waste. Individuals aware of buried radioactivity are assumed capable of identifying and managing radiological hazards. The limits for inadvertent intruders are 500 mrem for a single event up to five years in duration and 100 mrem yr^{-1} for chronic exposures to individuals occupying the site for longer periods. The intruder limits are assumed to be a TEDE.

The fourth performance objective requires that groundwaters are protected as required by all applicable regulations; however, there are no applicable groundwater protection standards for LLW disposed of at the Area 5 RWMS. The State of Nevada has promulgated standards for underground water and wells in Nevada Administrative Code (NAC) 534 and for public drinking water supplies in NAC 445. The latter standard includes the Environmental Protection Agency (EPA) National Interim Primary Drinking Water Regulations, 40 CFR 141, with additional state standards. The State of Nevada standards do not directly deal with protection of groundwater resources. The USDOE Nevada Field Office groundwater protection policy is to prevent or minimize the migration of pollutants to the groundwater while performing their mission of underground nuclear weapons testing (USDOE/NV, 1993b). The objective of this policy is to prevent groundwater contamination whenever possible. Characterization data for the uppermost aquifer indicates that the aquifer is a potential source of drinking water and preserving it as such is a conservative groundwater protection policy. Therefore, the adopted performance objective is that the uppermost aquifer is maintained to meet State of Nevada drinking water standards.

1.3.2 USDOE Order 5400.5, Radiation Protection of the Public and Environment

USDOE Order 5400.5 sets radiation protection standards for the public and environment. Standards applicable to LLW disposal are set for all USDOE exposure modes, airborne emissions, and the drinking water pathway. Standards covering management and storage of spent nuclear fuel, high-level, and TRU wastes (paragraph c.) are not applicable to LLW disposal. The applicable standards in USDOE Order 5400.5 are:

a. USDOE Public Dose Limit--all exposure modes, all USDOE sources of radiation. The exposure of members of the public to radiation sources as a consequence of all routine USDOE activities shall not cause, in a year, an effective dose equivalent greater than 100 mrem. The dose limits also apply to doses to individuals who are exposed to radiation or contamination by radionuclides at properties subsequent to remedial activities and release of the property.

b. Airborne Emissions Only, all USDOE sources of radionuclides. To the extent required by the Clean Air Act, the exposure of members of the public to radioactive materials released to the atmosphere as a consequence of routine USDOE activities shall not cause members of the public to receive, in a year, an effective dose equivalent greater than 10 mrem.

c. Not applicable.

d. Drinking Water Pathway Only, all USDOE sources of radionuclides. It is the policy of USDOE to provide a level of protection for persons consuming water from a public drinking water supply operated by the USDOE, either directly or through a USDOE contractor, that is equivalent to that provided to the public by the public community drinking water standards of 40 CFR 141. The liquid effluents from USDOE activities shall not cause private or public drinking water systems downstream of the facility discharge to exceed the drinking water radiological limits in 40 CFR 141.

The above requirements establish several performance objectives that must be considered in addition to those contained in USDOE Order 5820.2A. Paragraph (a.) of USDOE Order 5400.5 sets a dose limit of 100 mrem yr^{-1} for all USDOE exposures. Radionuclides attributable to NTS activities were not detected in the offsite monitoring network during 1992, the most recent year that data were available (USDOE/NV, 1993a). Offsite doses from NTS atmospheric emissions were estimated to be 0.01 mrem in the 1992 NESHAP compliance report (REECo, 1992). These data suggest that doses from NTS operations are currently negligible. Doses received by persons residing on the NTS after loss of institutional control are more difficult to predict. It has been assumed that all USDOE exposures from the NTS, excluding LLW, will amount to less than 75 mrem yr^{-1}. Therefore, the full 25 mrem yr^{-1} allowable for LLW disposal can be used as the performance objective. Paragraph (d.) specifically requires that drinking water supplies impacted by USDOE activities meet 40 CFR 141. As noted above, this standard has been adopted for the drinking water pathway.

1.3.3 40 CFR 61, National Emission Standards for Hazardous Air Pollutants

USDOE Order 5820.2A requires that airborne emissions meet the requirements of 40 CFR 61. Subpart H applies to emission of all radionuclides, other than radon, from USDOE facilities.

This standard limits radionuclide emissions to levels that would cause any member of the public to receive an effective dose equivalent of 10 mrem in any year. The standard is interpreted to be a TEDE in this assessment. Subpart Q applies to radon emissions from USDOE storage and disposal facilities for radium-bearing byproduct material. This standard limits average annual ^{222}Rn flux rates to 20 pCi m^{-2} s^{-1}.

Since USDOE Order 5400.5 requires that the sum of all sources meet these standards, the performance objective for LLW disposal may have to be reduced to allow for other airborne sources at the NTS. For 1992, the last year nuclear testing was conducted at the NTS, the effective dose equivalent received by an individual at the nearest residence via the air transport pathway was estimated by the EPA's CAP88-PC computer model to be 0.01 mrem (USDOE/NV, 1993a). Air monitoring results indicate that actual doses are much less. Since doses from all NTS airborne emissions appear to be insignificant, the full limit of 10 mrem yr^{-1} has been adopted as the performance objective for waste disposal. The Subpart Q radon flux standard has been adopted as the performance objective for radon emissions.

1.3.4 40 CFR 141, National Interim Primary Drinking Water Regulations

Drinking water supplies operated by the USDOE or impacted by USDOE effluents are to meet

Table 1.2. Summary of adopted performance objectives for the period of active institutional control.

Compliance Interval	Pathway	Compliance Point	Performance Objective
Period of Active Institutional Control	All Pathways (excluding airborne emissions)	Indian Springs, NV	25 mrem yr^{-1}
	Air Emissions (excluding radon)	Indian Springs, NV	10 mrem yr^{-1}
	Air Emissions (radon only)	Waste Cell Cap	20 pCi m^{-2} s^{-1}
	Groundwater	Uppermost Alluvial Aquifer	4 mrem yr^{-1}

Table 1.3. Summary of adopted performance objectives for the post-institutional control period.

Compliance Interval	Pathway	Compliance Point	Performance Objective
Post-Institutional Control	All Pathways (excluding airborne emissions)	Cane Springs and Indian Springs, NV	25 mrem yr^{-1}
	Air Emissions (excluding radon)	Cane Springs and Indian Springs, NV	10 mrem yr^{-1}
	Air Emissions (radon only)	Waste Cell Cap	20 pCi m^{-2} s^{-1}
	Groundwater	Uppermost Alluvial Aquifer	4 mrem yr^{-1}

Table 1.4. Summary of adopted performance objectives for inadvertent intruders.

Compliance Interval	Pathway	Exposure Mode	Performance Objective
Post-Institutional Control	All Pathways	Acute (<5 years) Chronic (>5 years)	500 mrem 100 mrem yr^{-1}

1.4 PERFORMANCE ASSESSMENT METHODOLOGY

The methodology employed for the preparation of the performance assessment has been to follow a logical sequence of steps as described by Case and Otis (1988). Performance assessment is an iterative process that proceeds sequentially from site characterization to conceptual model development, to outcome modeling and back to site characterization for the next cycle. This iteration or revision uses much of the methodology of earlier versions, but differs in the greater use of site-specific data for scenario development, model parameterization, and development of a refined conceptual model of the vadose zone.

The initial step in performance assessment is to set the scope of the analyses and identify the performance objectives. These activities have been documented in Chapter 1.

The next step is to document relevant site characterization data. This assessment describes and evaluates additional site characterization data as directed by the USDOE Peer Review Panel. Site characterization data has been documented in Chapter 2.

Chapter 2 also discusses the site inventory. The inventory used in this assessment has been limited to wastes disposed of from the implementation of USDOE Order 5820.2A. Raw inventory data obtained from the site database records have been critically evaluated and revised. However, the inventory data still contain significant uncertainties. A specific inventory has been analyzed to assure that there is a reasonable probability that past disposals can meet the performance objectives. Continuing assurance of compliance will be provided by developing radiological waste acceptance criteria based on this assessment and applying these limits to future disposals.

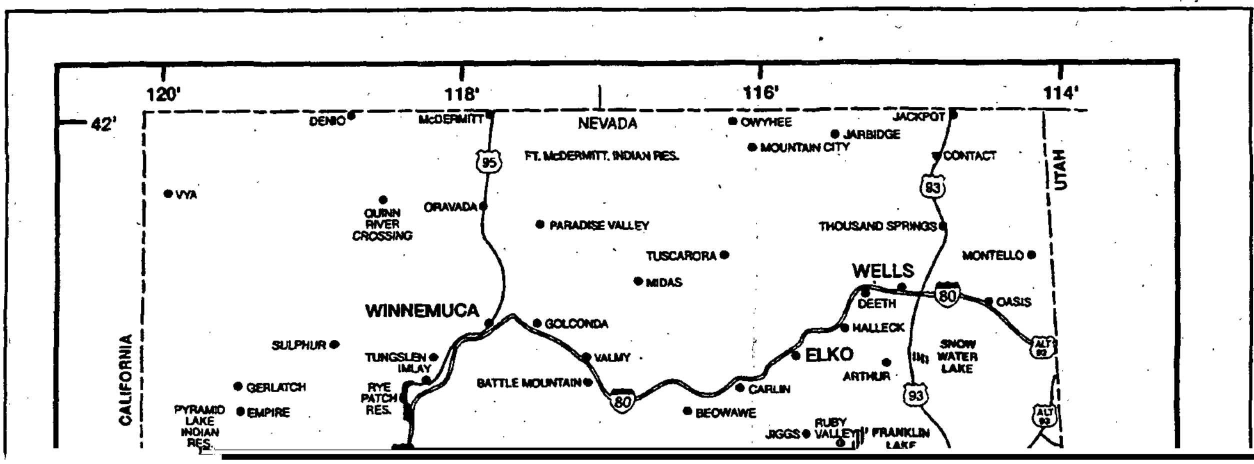
Chapter 3 describes the analyses conducted to assess compliance with the performance objectives. The analysis of performance begins with developing and selecting scenarios for evaluation. Several deterministic site-specific scenarios have been developed. A scenario is defined here as a description of all the features, events, and processes influencing the waste disposal system performance. Each scenario consists of several scenario modules that have a corresponding conceptual model and mathematical model. Scenarios are developed by preparing a comprehensive list of features, events, and processes. This list is then screened to remove processes or events that will not influence performance, are deemed physically improbable for the NTS, are extremely rare or improbable events, or are outside the scope of

2.0 FACILITY DESCRIPTION

2.1 GEOGRAPHY

The NTS is located in southern Nevada, approximately 105 km northwest of Las Vegas (Figure 2.1). Approximately 3,500 km^2 of land is encompassed by the current site boundary. The NTS is surrounded on the east, north, and west by two restricted access Air Force facilities, the (NAFBBGR) and the (TTR). The combined area of the NTS and the surrounding Air Force-controlled land, referred to as the NTS-NAFBBGR complex, is approximately 14,200 km^2. The NTS-NAFBBGR complex is isolated further by U.S. Department of Interior-controlled land that surrounds much of the complex. Counties falling within an 80 km radius of the Area 5 RWMS include portions of Nye, Lincoln, and Clark Counties in Nevada and Inyo County, California.

Las Vegas is the largest major metropolitan area near the NTS. Other population centers surrounding the NTS-NAFBBGR complex and their distances from the Area 5 RWMS are: Indian Springs (42 km), Lathrop Wells (52 km), Pahrump (80 km), Beatty (82 km), Alamo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TUSCARORA
MONTELLO
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GOLCONDA
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ARTHUR
GERLATCH
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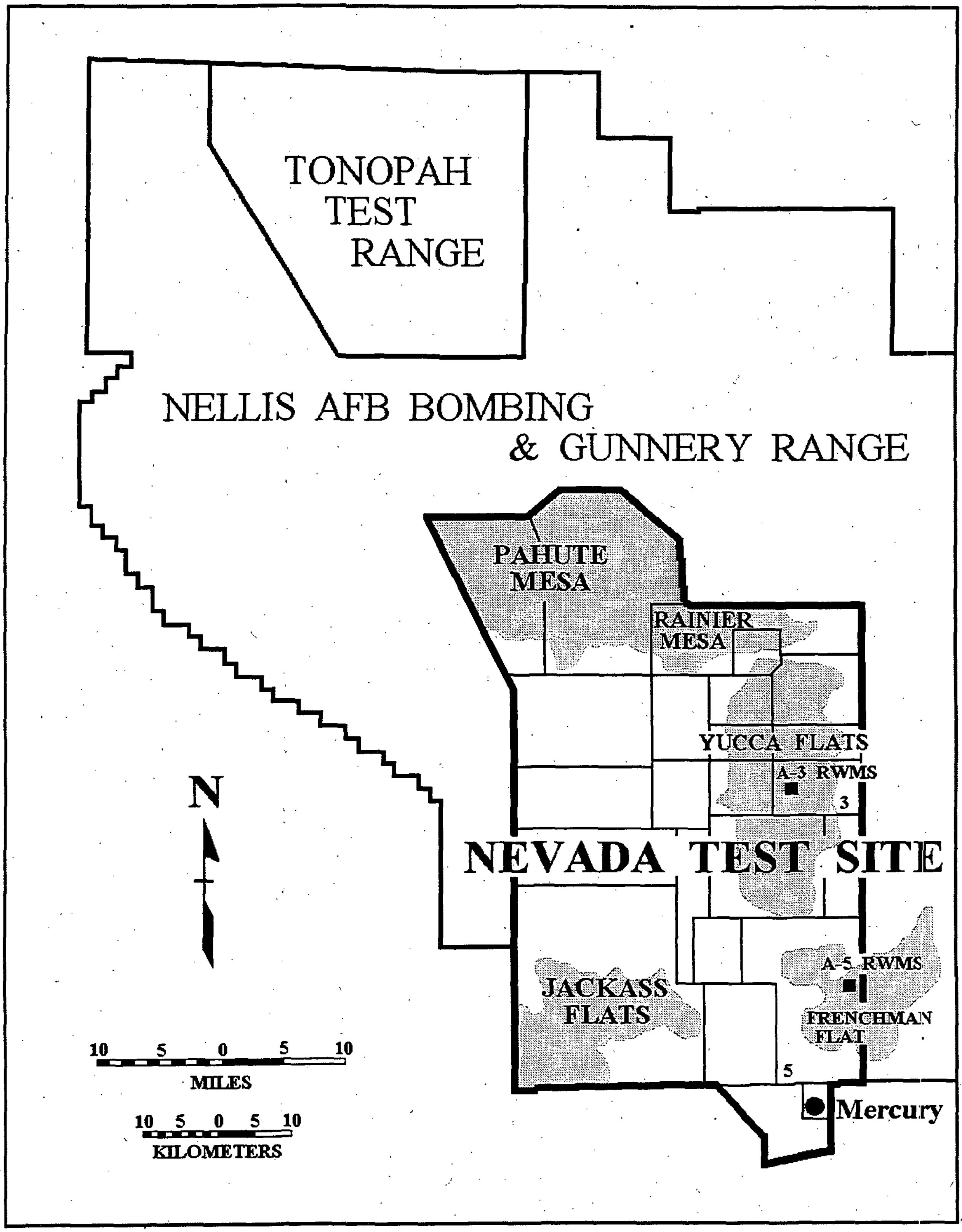


Figure 2.2 - Location of the Area 5 RWMS and major operational areas on the NTS.

by Mount Salyer. Frenchman Flat playa, a dry lake bed at the physiographic low of the basin (939 m above mean sea level), occupies approximately 14 km^2 and is perhaps the most prominent feature of the basin.

The Area 5 RWMS is located in the northern region of Frenchman Flat on three coalescing alluvial fans which extend southward from the Halfpint Range. The RWMS elevation ranges from 969 to 975 m above mean sea level. The RWMS is 3.8 km north of the playa and 30 to 36 m upslope of the playa.

The other major facilities within Frenchman Flat are the Liquified Gaseous Fuels Spill Test Facility (LGFSTF), located to the south on the playa, and the Device Assembly Facility (DAF), located approximately 10 km to the northwest. The LGFSTF is used for research on the atmospheric dispersion of volatile or gaseous hazardous materials.

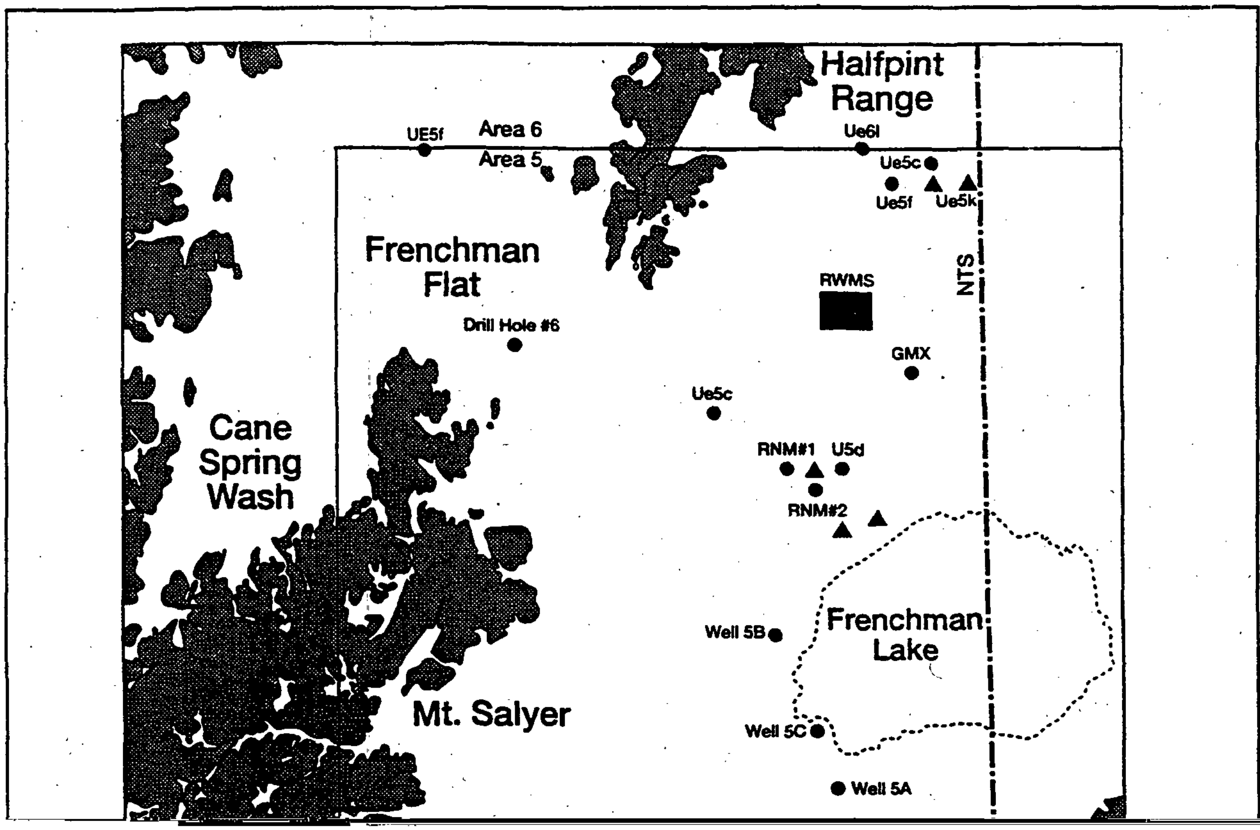
Frenchman Flat has been the site of 19 nuclear tests and several safety tests. Five underground nuclear tests have been conducted approximately 3.5 km to the south and 2.4 km to the northeast of the RWMS (Figure 2.3). Fourteen atmospheric tests were conducted over or in the immediate vicinity of the Frenchman Flat playa. Several safety tests have been conducted at the GMX site, 1.8 km to the southeast of the Area 5 RWMS.

2.2 METEOROLOGY AND CLIMATE

The climate and meteorology of the NTS and Frenchman Flat have been summarized previously by Winograd and Thordarson (1975), Case et al. (1984), Magnuson et al. (1992), and REECo (1993a).

2.2.1 Climatic Setting

The NTS lies within a region of the southwestern United States known for its arid intermountain deserts. Orographic lifting of humid Pacific air masses by coastal mountain ranges to the west causes a majority of the moisture destined for the continent to fall on the inter-coastal mountain ranges before reaching the interior. The NTS lies in a region that is transitional between the Great Basin Desert and the Mohave Desert. The climate is characterized by a large number of cloudless days, low precipitation, and high daily temperatures, especially in the summer. Death Valley, the driest region of the country, with summer temperatures greater than 49° C and an annual rainfall averaging 4.3 cm (Hunt et al. 1966), lies approximately 80 km to the southwest of the NTS.



Halfpint Range
UE5f
Area 6
Area 5
Ue6l
Ue5c
Ue5f
Ue5k
Frenchman Flat
RWMS
NTS
Drill Hole #6
GMX
Ue5c
Cane Spring Wash
RNM#1
U5d
RNM#2
Frenchman Lake
Well 5B
Mt. Salyer
Well 5C
Well 5A

2.2.2 Precipitation

Annual precipitation over the NTS ranges from 8 to 25 cm, depending on the elevation (Figure 2.4). Valley floors such as Frenchman Flat tend to be arid while higher mountains such as Pahute Mesa are sub-humid. The average annual precipitation in Frenchman Flat is approximately 12 cm. Table 2.1 summarizes the monthly precipitation for a 30-year period from January 1963 through December 1993 at Well 5B in Area 5.

Rainfall varies markedly with the seasons as well as with elevation. The majority of rain falls during two peak seasons, with a greater peak in the winter and a lesser one occurring during the summer months. This bi-modal precipitation pattern is the result of the formation of two distinctive global weather patterns that develop during the summer and winter quarters (Figure 2.5). During the summer, the lower Great Basin experiences frequent intrusions of

Table 2.1. Monthly precipitation (cm) for the period from January 1963 to December 1993 at Frenchman Flat (Well 5B).

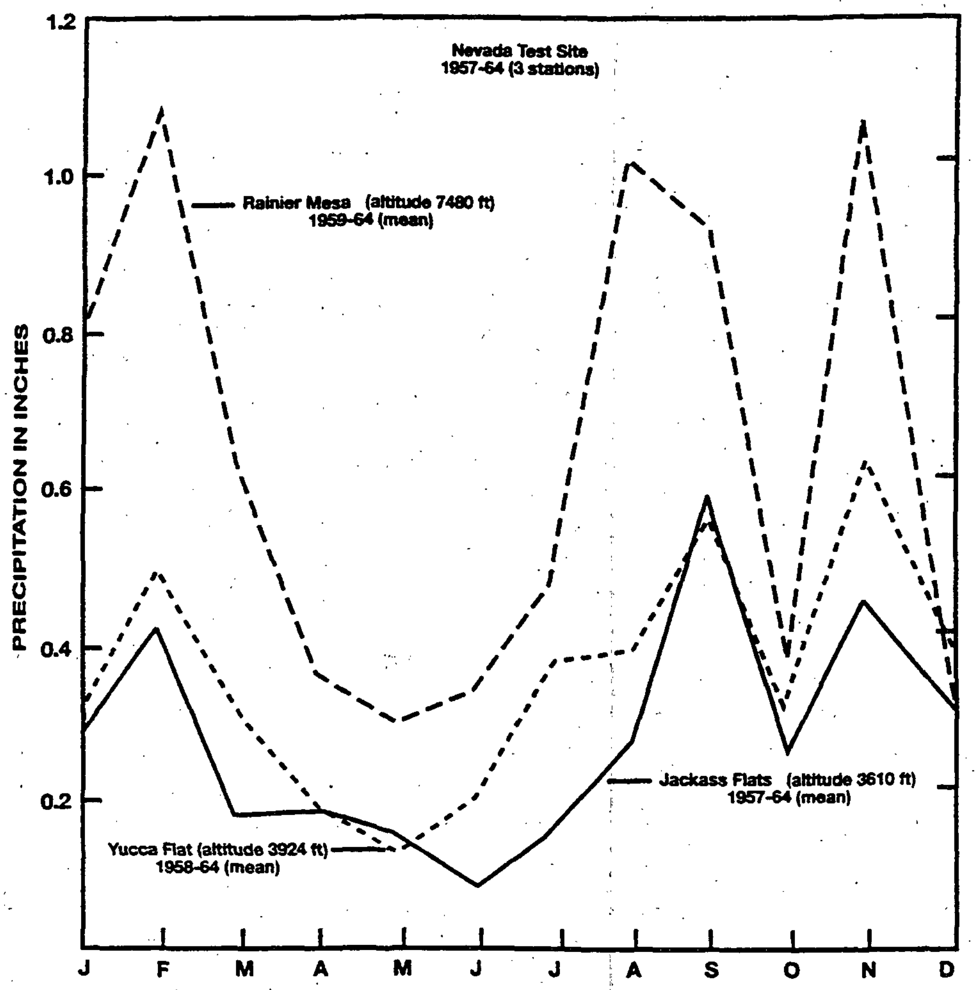
YR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
63	0.076	1.803	0.381	0.356	0.610	0.660	--†	0.889	5.486	0.508	1.676	0.051	12.497
64	0.356	--	0.838	1.270	0.229	0.686	0.305	1.676	--	0.178	0.356	--	5.893

Table 2.1. continued.

YR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
92	0.813	3.327	3.835	0.051	0.762	--	0.584	0.102	--	1.880	--	2.743	14.097
93	5.029	6.807	1.397	0.025	--	0.254	--	0.635	--	0.508	0.914	1.143	16.713
MEAN	1.575	1.499	1.397	0.737	0.762	0.305	1.067	1.346	0.940	0.635	1.092	1.219	12.548
MIN	--	--	--	--	--	--	--	--	--	--	--	--	2.896
MAX	5.029	7.087	6.096	4.216	5.004	2.235	6.655	9.500	5.486	2.870	3.531	5.791	23.419
SD	1.575	1.981	1.626	1.016	1.016	0.483	1.448	2.032	1.321	0.787	1.168	1.524	5.410

† "--" indicate zero precipitation.


38°00'
37°30'
Gold Flat
Kawich Valley



Normal and monthly mean precipitation at the NTS from 1957 to 1964 (Winograd and Thordarson)

Figure 2.5 - Monthly mean precipitation at the NTS from 1957 to 1964 (Winograd and Thordarson, 1975).

2.2.3 Temperature

NTS air temperatures vary highly with the seasons. Average daily temperatures range from 2° C in January to 24° C in August. Large daily fluctuations are common, especially on the playas and valley floors. Typical daily temperature ranges for the Area 5 RWMS run from −3 to 12° C in January, and from 17 to 36° C in July (Magnuson et al. 1992).

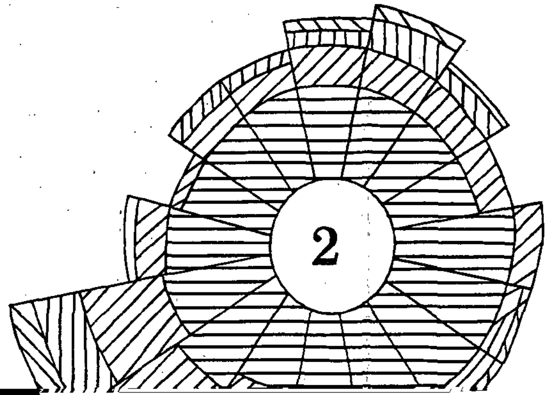
Due to the exposure of the ground surface to high levels of incident solar radiation and wind, the pan evaporation rate (potential evapotranspiration) at the NTS is very high. The estimated annual pan evaporation rate ranges from a minimum of 93 cm in January to a maximum of 595 cm in July with an average of approximately 310 cm, as measured by REECo on Frenchman Flat (1956-1958) and Jackass Flats (1967-1969) (Magnuson et al. 1992). Thus there are no permanent naturally occurring lakes or ponds within Frenchman Flat.

2.2.4 Wind

The directional wind patterns at the NTS vary according to three main mechanisms: (1) large scale movement of global pressure systems, (2) intermediate orographic effects due to regional mountain ranges, and (3) localized small scale convection currents due to nearby topography and terrain (Quiring, 1968). Northern winds tend to dominate in the winter and southern winds in the summer. Localized differential heating of the land surface during the day, coupled with a topographic trend toward greater elevation in the northern section of the NTS, result in southern winds flowing up slope during the day and northern winds moving down slope at night.

Wind speeds tend to be greater in the spring than in the fall. Because surface vegetation is sparse in the area, surface wind speed is categorized as calm only 2 percent of the time. Figure 2.6 summarizes the annual wind rose at Frenchman Flat for the years 1983 through 1993.

WIND ROSE
WELL 5B (W5B) ANNUAL 1983-93



2.3 GEOLOGY

2.3.1 Regional Geology

The NTS lies almost entirely within the Basin and Range physiographic province of the western United States. This province is part of the Intermontane Plateau unit of the Western Cordillera. The NTS rests on the edge of the transition zone between the stable craton to the east (Colorado) and the miogeosyncline to the west (Burchfiel et al. 1974), as evidenced by the stratigraphy in the nearby Spring Mountains.

The NTS lies near the western margin of the North American continent, in close proximity to southern California and its associated San Andreas Fault System. The San Andreas seismic zone is a large transform fault system within the continental margin which has historically exhibited a great deal of seismic activity. This tectonic setting and associated mountain building during the Cordilleran Orogeny (130 to 66 Ma) is responsible for

extensive thrust faulting, strike slip faulting, and block faulting throughout the Basin and Range Province.

Modern block faulting on an enormous scale has lead to the formation of numerous basins and ranges striking north-northeast throughout Nevada and the NTS (Zoback and Zoback, 1980). It is believed that the cause of this massive faulting is west-northwest to east-southeast deep crustal extension (Stewart, 1971; Zoback and Thompson, 1978; Wernicke et al. 1982; and Anderson et al. 1983); however, both the mechanism and the behavior of the faulting are still under debate (Brocher et al. 1993; Benz et al. 1990; Catchings and Mooney, 1991; Holbrook et al. 1991; Kruse et al. 1991). Whatever the mechanism, the geologic history of the Basin and Range Province has been long and complex. It is clear that a wide variety of rock types, both sedimentary and volcanic in origin and extending in age from Precambrian (570 Ma) to the present, have been subjected to deposition, compressive stresses, and extension on a very large scale (Judson et al. 1976; Allmendinger et al. 1987).

The regional geology within the NTS has been summarized in the work of Winograd and Thordarson (1975). Contributions by others regarding regional and site-specific issues includes the works of Carr (1974, 1984), Carr et al. (1967, 1975), Hudson (1992), Hoover (1968), Burchfiel (1964), Fleck (1970), Frizzell and Shulters (1990), RSN (1991a), Dozier and Rawlinson (1991), and Miller et al. (1993). These studies allow an interpretation or classification of the stratigraphy beneath the NTS, based on a hydrologic framework, into eight primary units with associated lithologic character. These units were deposited over long periods of geologic time, under varying depositional environments. The lithologies range from clastic and carbonate rocks in the bottom sections to volcanic clastic deposits of ash-fall and ash-flow tuff, rhyolites, and basalts in the upper sections. The topmost unit on which the Area 5 RWMS is located consists of unconsolidated valley fill alluvium. A summary of the general stratigraphy beneath the NTS, including lithologies and mode of emplacement, appears in Appendix B.

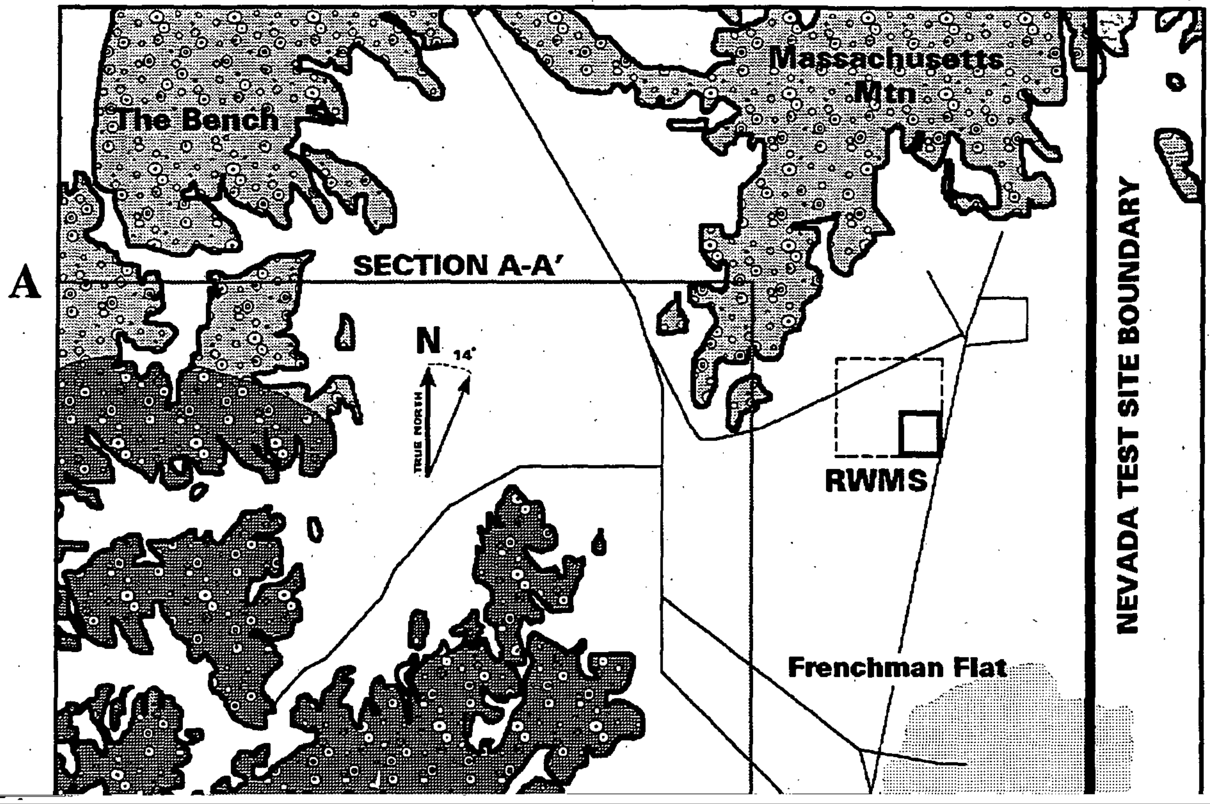
2.3.2 Geology of Frenchman Flat and the Area 5 RWMS

Frenchman Flat is a closed basin bounded by the Halfpint Range to the north, the Ranger Mountains and the Spotted Range to the east-southeast, and Mount Salyer to the west (Figure 2.7). It ranges in elevation from approximately 1,600 m above mean sea level in the surrounding mountain ranges to 940 m at its lowest point, a dry lake bed, known as the Frenchman Flat playa or Frenchman Flat Lake. The Frenchman Flat basin is filled with alluvial sediments up to 600 m deep at their thickest point. The basin drains a 1,200 km^2 watershed.

2.3.2.1 Structural Features

Carr (1974) outlined the early structural development of the northern portion of Frenchman Flat. The early structural development is attributed to late Pliocene movement along several major fault systems associated with the initiation of Basin and Range tectonics. These systems include the Cane Springs Fault and the Rock Valley Fault Systems (Figure 2.8). Later, during the early and middle Tertiary, the valley continued to widen as ash-flow and ash-fall tuffs were deposited. The Cane Springs Fault plays an active role in the continuing development of the basin (Carr, 1974), although the rate of basin subsidence is unknown (RSN, 1991a).

The Area 5 RWMS appears to lay upon a stable downthrown block, surrounded by nearby seismic features. Locally active faults near the Area 5 RWMS include the Cane Springs and Rock Valley Fault Zones (Figure 2.8). The Cane Springs Fault Zone, a left-lateral strike-slip fault trending northeast, lies approximately 6.4 km to the west-northwest of the RWMS. The younger Rock Valley Fault System (Holocene) also trends to the northeast but exhibits more dip-slip characteristic of block faulting. This zone to the south of the Frenchman Flat playa, approximately 9.6 km from the RWMS. The so called Frenchman Flexure Zone, a northwest trending pattern of arcuate structure approximately 6.5 km northwest of the



A
The Bench
Massachusetts
Mtn
SECTION A-A'
N
14°
TRUE NORTH
RWMS
Frenchman Flat
NEVADA TEST SITE BOUNDARY

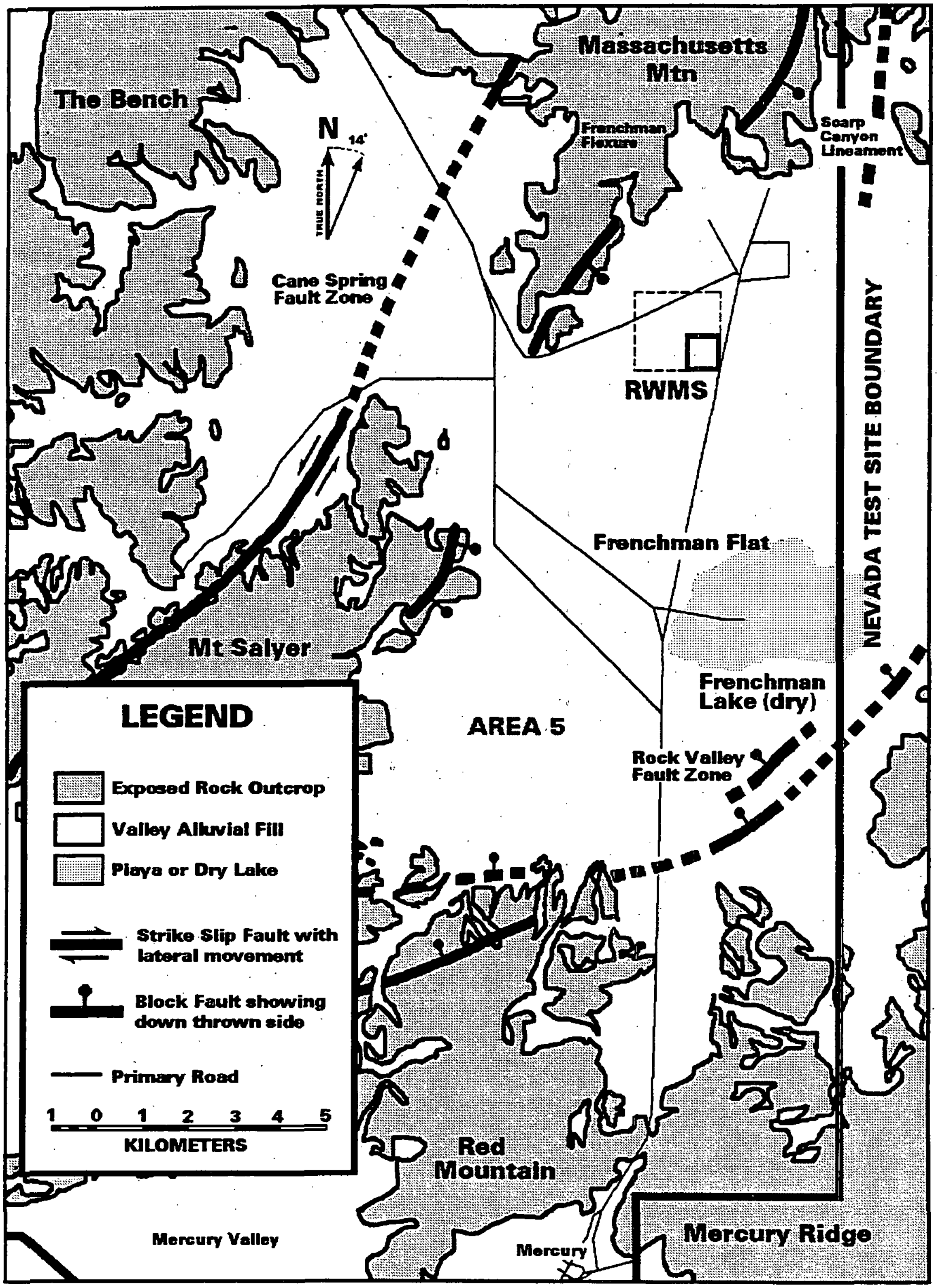


Figure 2.8 - Map showing the major structural features of the Frenchman Flat Basin in the vicinity of the AREA 5 RWMS.

RWMS in the southern extreme of the Halfpint Range, has been shown by Hudson (1992) to be an artifact of stress caused by adjoining blocks rather than a major structural feature in the area.

A number of lineaments are apparent within the northern portion of Frenchman Flat (Miller et al. 1993). Continuing studies by Raytheon Services Nevada (RSN) (1993) are investigating their occurrence and possible impact on the RWMS' ability to comply with the surface-fault-related disposal criteria set forth by the Resource Conservation and Recovery Act (RCRA) under 40 CFR 264.18. Part of the assessment includes an examination of the apparent faulting in Scarp Canyon and other erosional features in the vicinity of the RWMS. A review of borehole logs and reports (as well as magnetic, gravity, and resistivity surveys) may suggest the presence of buried linear anomalies near the RWMS. Evidence suggesting faulting in the area of the RWMS was found with a high-resolution CSAMT (controlled source audio-frequency magnetotellurics) survey by Zonge Engineering (1990). This report described a conductor at a depth of 500 m that may be interpreted as saturated ash-flow tuff, which appears to show some form of discontinuity.

To help identify faults of regulatory significance that could impact the facility, lineaments have been mapped using remotely sensed data (Miller et al. 1993). These data include color and infrared aerial photography, and side-looking airborne radar images. To date however, the only lineament confirmed to be fault-related and associated with surficial deposits is located 3.5 km northwest of the RWMS in the longitudinal valley of the Massachusetts Mountains, part of the Halfpint Range. The faulting is estimated as late-Tertiary to Quaternary in age, based on faulting of conglomeritic alluvium overlying an ash deposit tentatively correlated with the Frenchman Flat Ash, which is estimated to be older than 2.9 Ma (Izett, 1988). Excavations and trenches to the northeast of the RWMS did not identify any surficial faulting associated with erosional scarps in the area, (RSN, 1993), nor was any evidence of faulting uncovered during mapping of alluvium in pit walls within the RWMS (Snyder et al. 1993).

2.3.2.2 Potential for Seismic Activity

Rogers et al. (1977), Campbell (1980), Battis (1978) and Hannon and McKague (1975) have conducted seismic hazard studies of the NTS. They agree that the predicted maximum magnitude for an earthquake ranges from 5.8 to 7.0, with peak accelerations of 0.7 to 0.9 g. The estimated return period for the largest amplitude earthquakes expected (5.8 to 7.0) ranges from 12,700 to 15,000 years. These data suggest that there is the potential for a large earthquake somewhere within the NTS during the next 10,000 to 15,000 years.

The probability of the occurrence of at least one earthquake greater than 6.8 on the Richter scale is estimated in Appendix B. These calculations suggest there is about a 50 percent chance of one or more earthquakes greater than 6.8 in the next 10,000 years.

Despite the moderate risk of seismic activity, the limited use of engineered structures at

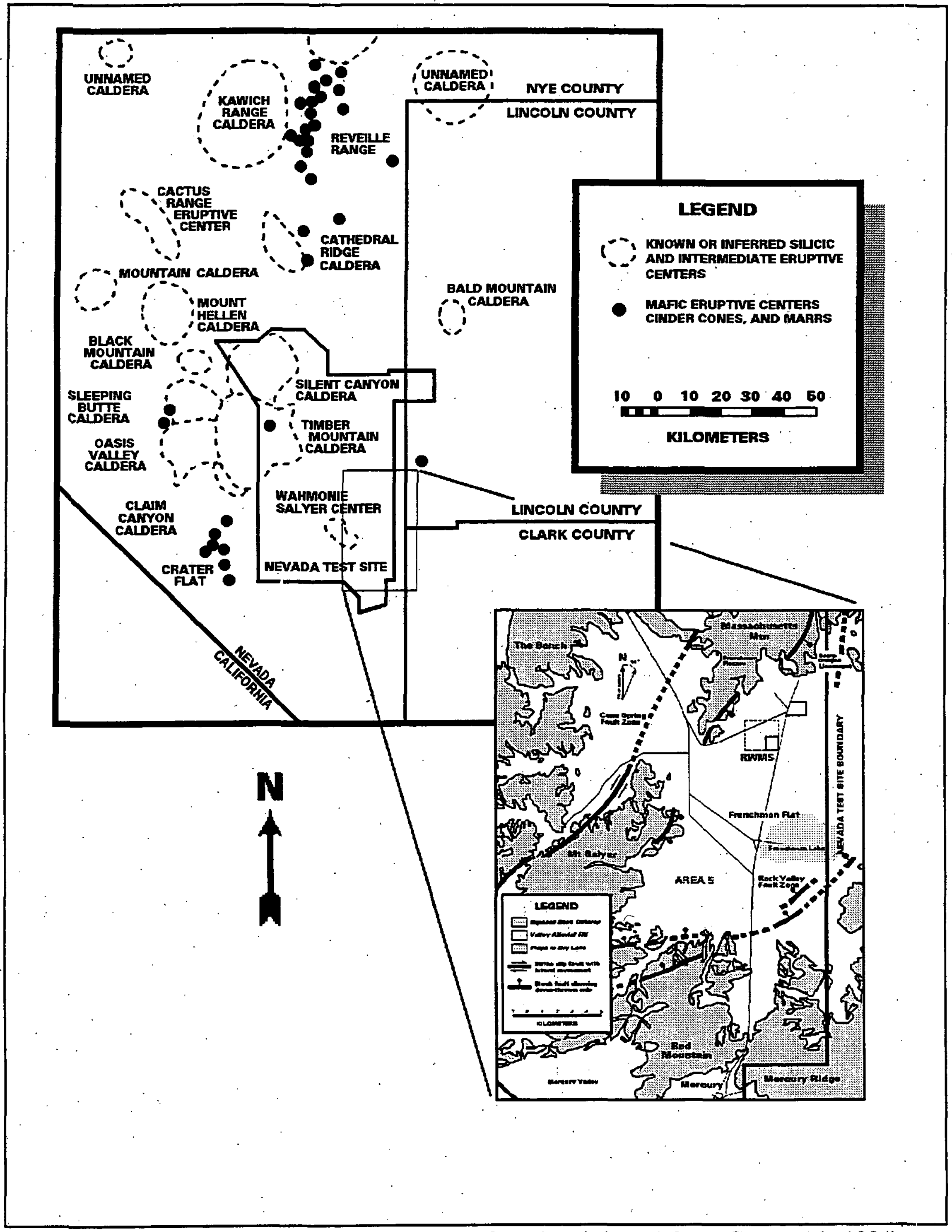


Figure 2.9 - Tertiary volcanic centers in the NTS region (adapted from Case et al. 1984).

flow was encountered 268 m below the surface in borehole UE5i, and a basalt rubble was found about 275 m below the surface at borehole UE5k (Figure 2.3). The location of the eastern edge of the flow was determined by geophysical means (Carr, 1974). The ages of the basalt in UE5i and UE5k have been established at 8.6 and 8.4 Ma respectively (RSN, 1994).

Data concerning the hazards of future volcanism in the NTS region have been acquired from ongoing assessments of the volcanic hazard at Yucca Mountain. These data have been used to assess the potential for renewed volcanic activity in Appendix B. This analysis indicates that volcanism is unlikely to have any impact on the integrity of the Area 5 RWMS over the next 10,000 years.

2.3.2.4 Local Stratigraphy

The stratigraphy of rock units from the surface to the lower carbonate units directly beneath Frenchman Flat is known to a reasonable degree based on both surface and subsurface investigations. These include numerous borehole descriptions collected to support underground testing, published well logs collected near the Area 5 RWMS (RSN, 1991b), core cuttings from the Pilot Wells (REECo, 1993b), investigations of surficial geology (RSN, 1991a; Frizzell and Shulters, 1990), CSMAT surveys (Zonge Engineering, 1990), and gravity data (Miller and Healey, 1965).

Subsurface Observations

The Area 5 RWMS is built upon alluvium derived in part from the Tertiary volcanic rock exposed in the nearby Massachusetts Mountains and the Halfpint Range, as well as carbonates, quartzites, and other sedimentary rocks from the Nye Canyon area (Snyder et al. 1994). The thickness of the alluvium varies from zero at the edges of the basin to approximately 600 m in the center near the Frenchman Flat playa. The alluvial sediments are estimated to be Middle Miocene to Quaternary in age. The thickness of the alluvium is estimated to be between 360 and 460 m thick directly beneath the Area 5 RWMS.

Beneath the alluvium lies a layer of interbedded Tertiary ash-flow and ash-fall tuff, estimated to be over 550 m thick. Well log data suggest that these units are predominantly Timber Mountain ash-flow tuff and tuff of the Wahmonie Formation (RSN, 1991b). More recently, site characterization studies (REECo, 1993b) identified lithologies, similar to the Ammonia Tanks Member of the Timber Mountain Tuff, 180 m beneath the surface in Pilot Well UE5PW-3, which is located approximately 1.8 km to the northwest of the active RWMS

(Figure 2.19). The thick wedge of ash-flow and ash-fall tuff is underlain by an undetermined thickness of Paleozoic carbonate rocks and other lithologies down to the Precambrian basement.

Basalt flows found to be overlying alluvial sediments in boreholes UE5i and UE5k have been dated to be 8.6 and 8.4 Ma old. The accumulation of sediment beneath the basalt suggests that the basin was present in some form and was accumulating sediment prior to about 8.5 Ma. Also, the occurrence of the basalt at a similar depth in boreholes 2 km apart suggests that either the basalt layer is on a single fault block or that minimal fault activity has taken place since emplacement (Snyder et al. 1994).

The upper surface of the basement carbonate and clastic rocks in Frenchman Flat has been estimated from gravity data (Miller and Healey, 1965) to be 1,400 ± 150 m deep in the north-central portion of the basin. This gravity minimum in the north-central portion of the basin (Figure 2.10) does not correspond to the present day topographic low at Frenchman Flat playa, indicating that the thickest section of alluvium in the basin lies a few thousand meters southeast of the RWMS. The gravity data suggest that the upper surface of the carbonate is approximately 1,340 ± 150 m below the surface at the Area 5 RWMS.

Near-Surface Observations of Alluvial Sediments

The near-surface stratigraphy of alluvial sediments has been studied in detail to a depth of approximately 11 m (RSN, 1991a; Snyder et al. 1993). The near-surface structure displays features expected for lower-middle to distal alluvial fan deposition, including sheet-flood, stream channel, and debris flows. A grain-size analysis reveals alternating sequences of fine and coarse grained sediments, with occasional lenses of very coarse stream channel deposits (RSN, 1991a). All of the deposits are unconsolidated and were caused by water-based deposition. The debris is composed predominately of pyroclastic tuff clasts with lesser amounts (averaging 5 to 10 percent) of non-volcanic clasts. The lithology of the deposits, combined with paleo-flow estimates, suggests that deposition was from the north or northeast, e.g. the Scarp Canyon and Nye Canyon watersheds are the source for most of the sediments.

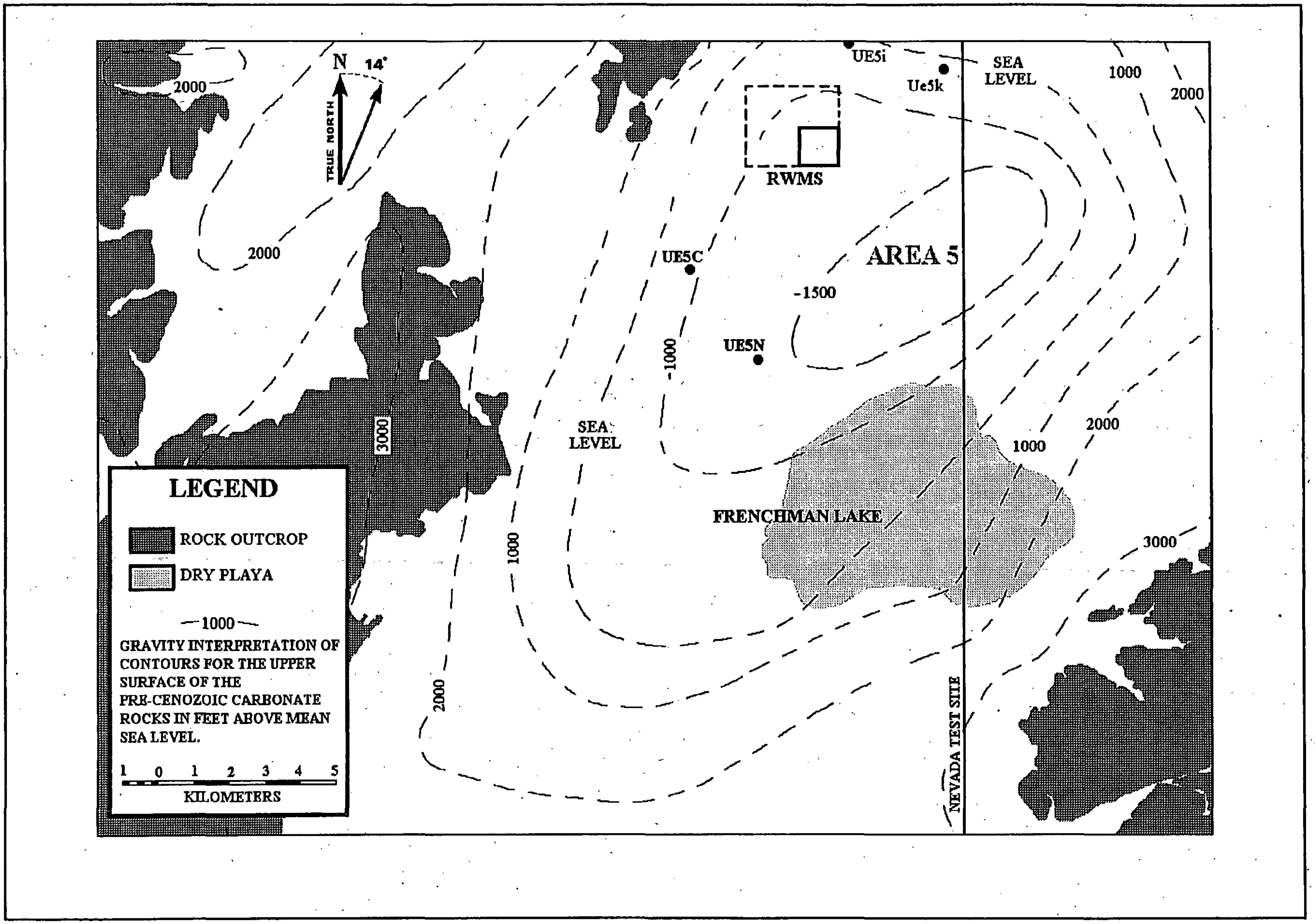


Figure 2.10 - Gravity interpretation of the elevation of the top surface of the carbonate section underlying Frenchman Flat (adapted from Miller and Healey, 1965).

Six allostratigraphic units have been identified and mapped in the vicinity of the Area 5 RWMS. These units were found to be remarkably continuous both along pit walls and among the pits, although they varied internally somewhat according to grain size, sorting, clast abundance, and bedding. Sedimentary structures are common in the deposits observed in the waste pits and trenches and consist of two types: (1) depositional structures, or those

cut-and-fill) and (2) post-depositional structures such as animal burrows, roots, or rhizoliths. Planar-bedding is much more common than cross-bedding in the sheet-flow deposits at the RWMS, and may indicate the occurrence of relatively high-velocity flow events in the past. Some accumulation of calcium carbonate, in the B and BC horizons as coatings on clasts and with pendants of pebbles and sand beneath, indicates repeated periods of surface stability in the Quaternary.

Particle Size Analysis

Particle size distribution can influence the hydraulic conductivity of porous media, and reflects the uniformity of an aquifer material. Particle size analysis by both the wet and dry sieve methods were performed on drill cuttings and core samples from all three Pilot Wells (REECo, 1993b). The particle size analysis was limited to material less than the size of the core diameter (e.g., cobbles or boulders larger than approximately 0.09 m are not recovered in core samples).

Interpretation of the vertical distribution of gravel, sand, and fines within the three Pilot Wells varies according to perspective, hydrologic or geologic. When the data are smoothed to remove spikes from local heterogeneities, UE5PW-1 and UE5PW-3 exhibit an overall fining upward sequence, and UE5PW-2 appears to have two fining upward sequences, one from 125 m to the surface, and another from the bottom of the borehole to 125 m. In a gross sense, with the exception of UE5PW-2, the profiles are essentially constant with depth, both within and among the wells as shown in Figure 2.11. Table 2.2 shows the relative percent of materials falling into the gravel, sand, and silt/clay size fractions, which were determined from analyses on 2,100 core samples at 0.76-m intervals from the Science Trench Boreholes (REECo, 1993c).

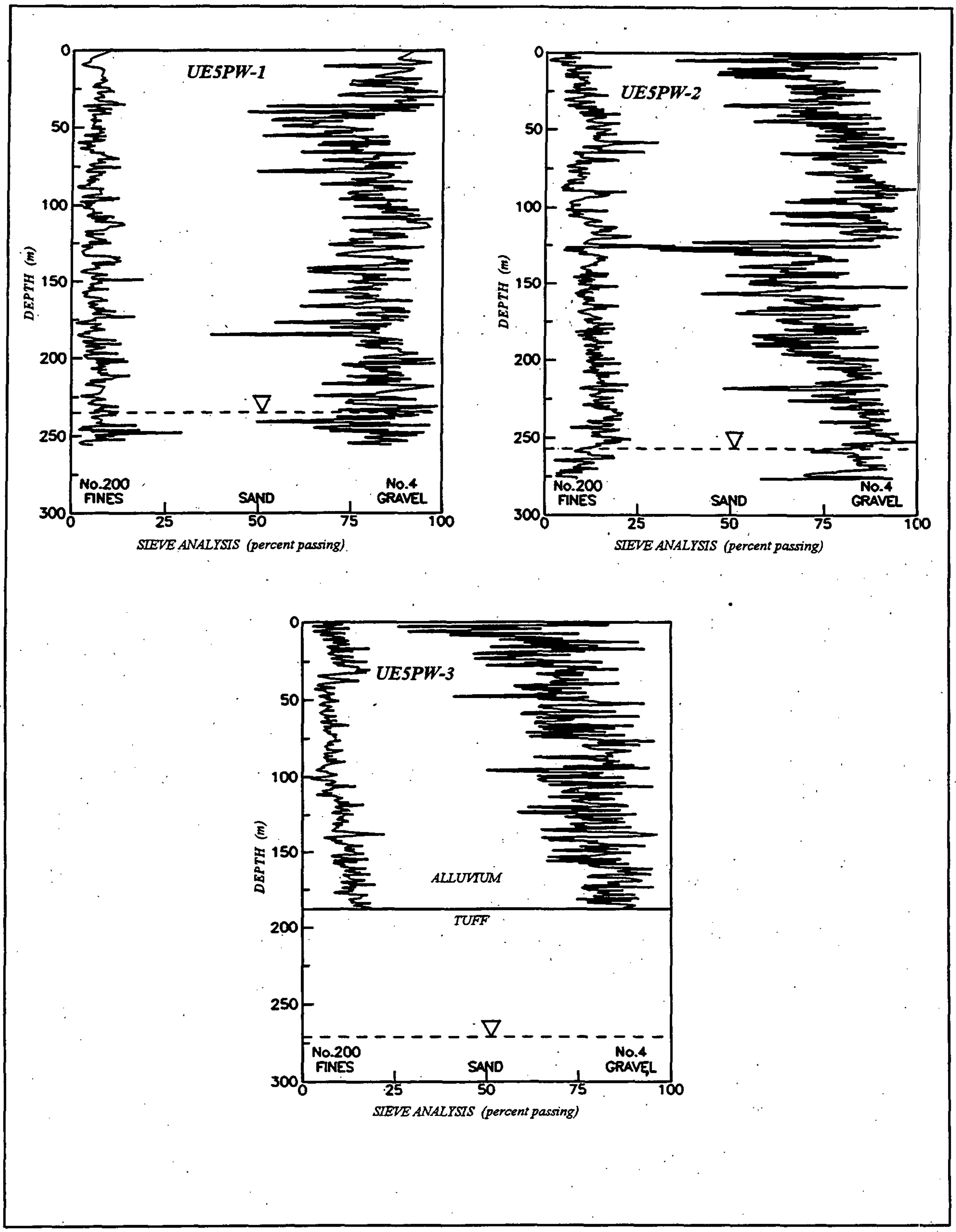


Figure 2.11 - Depth profile for the grain-size distribution (Unified Soil Classification System) in the three Pilot Wells (REECo, 1992b).

The alluvium composition was estimated to be 20 percent gravel, 70 percent sand, and less than 5 percent silt. Figure 2.12 compares the grain-size distribution of the alluvium to typical distribution curves for soils (Bear, 1972) as classified by the U.S. Department of Agriculture. Using this chart, the alluvium can be characterized as a well-graded, medium sand with gravel and lesser amounts of silty clay-sized material. The silty clay-sized fraction is composed primarily of silt rather than clay according to analysis by hydrometer. Individual particle density analyses on samples from the Science Trench Boreholes yielded a

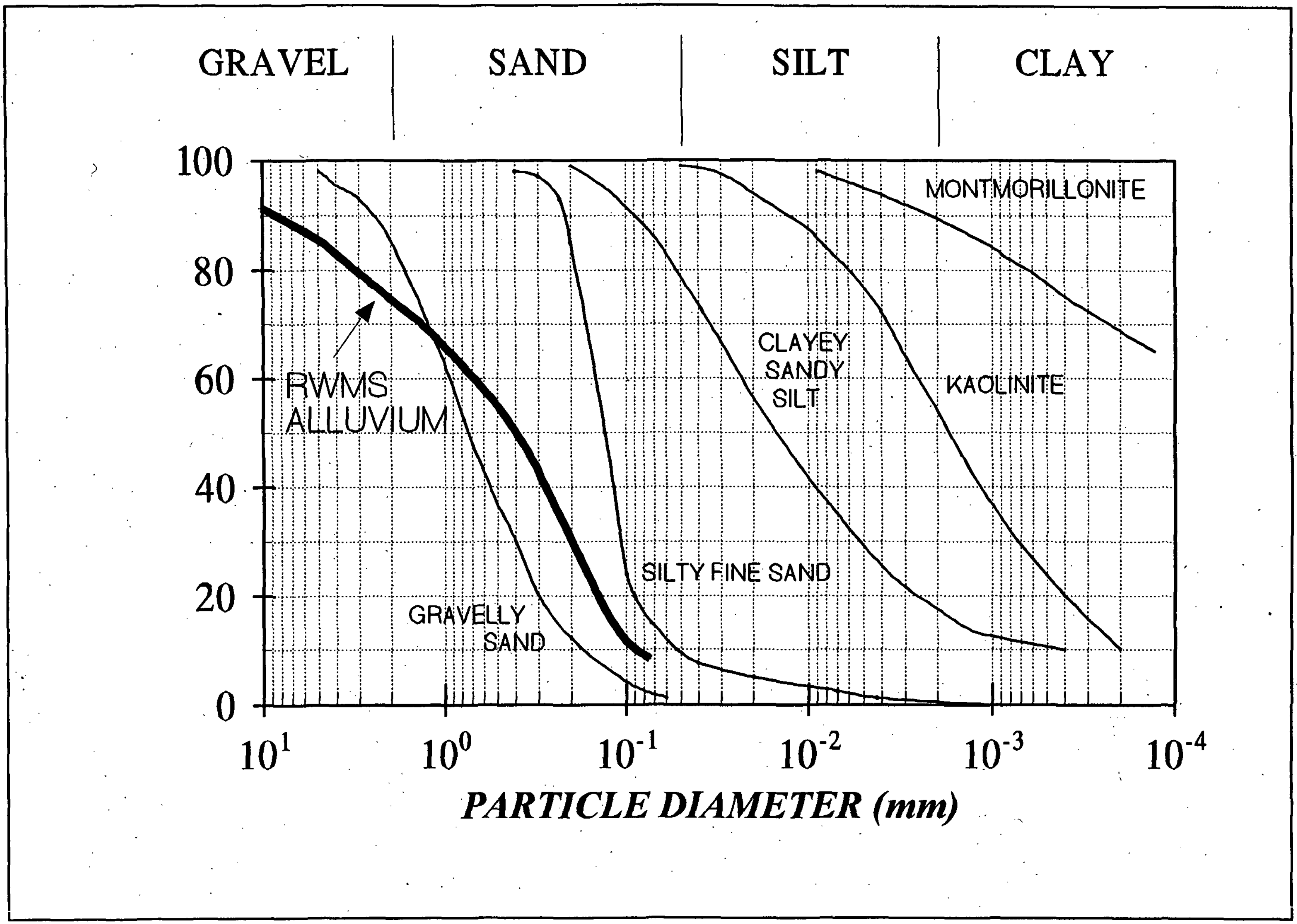


Figure 2.12 - Area 5 RWMS gross mean particle size distribution in comparison to other typical soils analyzed by the U.S. Department of Agriculture (adapted from Bear, 1972).

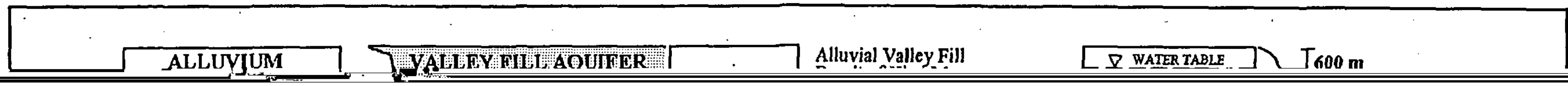
with water. In general, there exists an inverse relationship between the thickness of an unsaturated zone and the amount of precipitation available on the surface. This relationship holds true at the NTS, where annual rainfall is small and the unsaturated zone is very thick. Winograd and Thordarson (1975) found that the depth to saturation (excluding any perched water) varies from 200 to 600 meters below the valley floors and even more below mountain ridges.

Beneath the unsaturated zone and the water table lies the saturated flow regime. At the NTS, infiltration from above and from horizontal movement within the aquifer itself is a function of the proximity of the aquifer to the surface and the lithology of the overlying rock units.

2.4.1.2.1 The Saturated Flow Regime Distribution and Character of Principal Aquifers and Aquitards

The lithology and structure of the stratigraphy beneath the NTS play an important role in the occurrence and movement of groundwater flow. Winograd and Thordarson (1975) characterized the hydrologic properties of the geologic section into several aquifers and aquitards, based on their lithology and water-bearing characteristics, as shown in Figure 2.13. It should be emphasized that Figure 2.13 is a highly idealized conceptual perspective on a very complex region. Because of erosion and structural deformation, both the stratigraphic section and the idealized hydrogeologic sections shown may not exist in their entirety within the NTS. For example, near Mercury Ridge the structural deformation and erosion of overlying layers have exposed the lower clastic and carbonate rocks at the surface. In other areas, the upper carbonate and clastic rocks are completely absent (see Frizzell and Shulters, 1990). The only lithologic units with extensive areal coverage and subsequent control of deep regional groundwater movement are the lower clastic aquitard and the lower carbonate aquifer.

The extensive structural and erosional history of the stratigraphic section has resulted in a highly variable distribution of hydrologic units from basin to basin within the NTS. A unit forming a thick unsaturated outcrop on a ridge may be deep in the saturated zone in an adjacent valley. This can be observed in the northwest portion of the NTS, which is characterized by high mesas outcrops of lava and ash-flow tuff. Some units which form outcrops on the mesa are buried beneath 1,000 or more meters of alluvium in Yucca Flat and Jackass Flats. Further south and east, in the vicinity of Frenchman Flat, tuff is completely absent on the ridges near Mercury, where erosion and folding have exposed the Paleozoiccarbonates. Thus it is apparent that both the surface and subsurface extent of the hydrogeologic units presented in Figure 2.13 vary from valley to valley throughout the NTS.



ALLUVIUM
VALLEY FILL AQUIFER
Alluvial Valley Fill
WATER TABLE
600 m

The deepest saturated flow regime occurs in the lower carbonate aquifer. Although other stratigraphic units play some role within the saturated flow regime at various locations within the NTS, the lower carbonate aquifer provides the primary drainage for a large number of interconnected basins. This drainage occurs by horizontal movement of water through primary interstices and fractures in response to a largely horizontal hydraulic gradient at depth. The aquifer is generally confined above by either the upper clastic or bedded tuff aquitard, except where it occurs near the surface in outcrops such as in the ridges near Mercury. The aquifer is replenished primarily through horizontal flow from adjoining valleys and limited vertical flow from overlying strata. In general, the regional saturated subsurface hydrology in the NTS is dominated by deep horizontal flow within this aquifer, which is overlain by a thick zone of unsaturated media of varying lithologies.

Figure 2.13 shows the four primary lithologies controlling the movement and occurrence of groundwater at the NTS: valley fill alluvium, tuff, clastic rocks, and carbonate rocks. The ability of each rock to store and transmit water is a function of the available primary interstitial porosity and secondary openings, joints, and fractures. In general, alluvium, welded tuffs, and carbonates form aquifers whereas the bedded tuffs and clastic rocks tend to form aquitards that retard water movement.

Winograd and Thordarson (1975) have described suites of rock facies and lithologies which exhibit similar hydrologic character. These hydrologic units are presented below from the bottom to the top, oldest to the youngest. Interstitial porosities and hydraulic conductivities of these units are summarized in Table 2.3.

Table 2.3. continued.					
REGIONAL POROSITY AND PERMEABILITY					
Welded Tuff Aquifer	3-48	-	3.8-5.1	-	moderate
Lava Flow Aquitard	5.7-14.1	-	-	-	low
Bedded Tuff Aquitard	10.8-48.2	37.7	-	0.006	low

saturation. Elsewhere within the NTS, the unit is under saturated confined conditions deep beneath overlying units of limestone and tuff. The unit has not been penetrated by any wells within Frenchman Flat or in the vicinity of the Area 5 RWMS, but it is believed to exist beneath the carbonate aquifer at great depth.

Lower Carbonate Aquifer

Nine formations composed primarily of limestone and dolomite are classified within this sequence. The units range from the lowermost Carrara silty-limestone formation, which forms a transition zone to the clastics just described, to the highly permeable Devils Gate limestone. The carbonate unit primarily lies deep within the saturated zone at the bottom of the stratigraphic column beneath practically all the basins including Yucca Flat, Jackass Flats, and Frenchman Flat. Winograd and Thordarson (1975) also noted that, due to thrust faulting, low-angle normal faulting and the existence of the extensive caldera complex to the northwest of the NTS, the carbonate aquifer underlying most of the NTS may not be hydraulically continuous with the same units to the northwest (if, indeed, they do exist beneath the calderas).

The lower carbonate aquifer is unsaturated only where it outcrops as topographical highs, such as in the Halfpint Range, Ranger Mountains, and ridges near Mercury in the east and southeast portions of the NTS (Figure 2.7). Although the lower carbonate aquifer has experienced the same degree of deformation, fracturing, and brecciation as the underlying lower clastics, the fractures and joints have not experienced the same degree of cementation and thus are much more permeable to groundwater flow.

The average intercrystalline matrix porosity of the carbonates is very low. It has been estimated from core samples by Winograd and Thordarson (1975) at 5.4 percent, with a range from 0.4 to 12.4 percent. Winograd and Thordarson also determined the

Winograd and Thordarson (1975) that the wide variation in transmissivity could be the result of structural differences within the aquifer rather than changes in bulk lithology. This is because the observed variation occurred in five wells known to tap the aquifer in the upper brecciated plate of a low-angle thrust fault. Despite these local variations, there is evidence that the fracture transmissivity of the lower carbonate aquifer as a whole may be homogeneous, even though it exhibits local inhomogeneities. Winograd and Thordarson (1975) showed semilog time-drawdown curves for various wells where the second limb exhibited a constant slope, resembling curves for a grossly homogeneous aquifer. This conclusion is supported by model studies of Warren and Price (1961) and Parsons (1966).

The lower carbonate aquifer plays a very active role in the deep regional saturated hydrologic regime because of its great thickness, hydrologic characteristics, and extensive areal coverage. There are three sources of recharge for the aquifer: (1) precipitation at high elevations where the aquifer outcrops at the surface, (2) downward leakage of water from the overlying Cenozoic hydrologic units, and (3) lateral underflow into the aquifer from outside the immediate region. Downward leakage from overlying hydrologic units is considered secondary to the other sources of recharge, and has been estimated to be 1 to 5 percent of total recharge (Winograd and Thordarson, 1975).

Upper Clastic Aquitard

The upper clastic aquitard consists of the entire thickness of the Eleana Formation. Because of its limited extent, the aquitard is hydrologically important only beneath the western portion of Yucca Flat and northern Jackass Flats, where it is fully saturated and is more than 1,000 m thick. In this location, it hydraulically connects the upper and lower carbonate aquifers; elsewhere within the NTS, it has either been completely eroded or occurs far above the regional water table (Winograd and Thordarson, 1975).

The total interstitial porosity ranges from 2.0 to 18.3 percent, with an average of 7.6 percent. Similar to the lower clastic aquitard, it is believed to exhibit little to no fracture permeability.

Upper Carbonate Aquifer

The upper carbonate aquifer is composed of only one unit, the Tippipah Limestone. Similar to the upper clastics, it is only of hydrologic significance beneath the western one third of Yucca Flat (at an elevation below 1,160 m), where it is saturated. Otherwise, it has been completely eroded or occurs in mountain ridges well above the regional water table

(Winograd and Thordarson, 1975). It is presumed that the hydrologic characteristics of the unit are similar to those of the lower carbonate aquifer. Because of its extremely limited occurrence, the upper carbonate aquifer does not play a role in the regional interbasin flow regime beneath the NTS.

Bedded Tuff Aquitard

The bedded tuff aquitard (Figure 2.13) is comprised of a thick sequence of seven tuff units.

structural lows, such as Frenchman Flat, it is estimated to be in excess of 1,370 m thick beneath the alluvium. Because of its relatively large areal extent and thickness, it may be a major barrier within the saturated zone, preventing large scale movement of water into the more permeable carbonates below.

Lava Flow Aquitard

The lava flow aquitard is composed of dacite lava flows of the upper Wahmonie Formation. It is restricted to a small area in the central portion of the NTS north and west of Mount Salyer and the Cane Springs Fault (Figure 2.8). Occurrence and movement of groundwater within the unit is observed only on a highly localized scale, primarily through fractures.

Although the estimated hydraulic conductivity may be as high as 20 m day^{-1}, evidence suggests that the gross conductivity is much less, due to the occurrence of perched water (Winograd and Thordarson, 1975). The interstitial porosity of the flows ranges from 5.7 to 14.1 percent (Johnson and Ege, 1964).

Welded Tuff Aquifer

The welded tuff aquifer includes the Topopah Spring and Tiva Canyon members of the Paintbrush Tuff, and the Rainier Mesa and Ammonia Tanks members of the Timber Mountain Tuff (Figure 2.13). Although the aquifer extends throughout the NTS, it is important only for the deepest portions of a few basins where it occurs within the saturated zone, often beneath valley fill alluvium. The aquifer is believed to underlie a portion of the alluvium upon which the Area 5 RWMS sits, as evidenced by outcrops in the nearby Massachusetts Mountain and core data from Pilot Well UE5PW-3, located approximately 2 km northwest of the site.

As the name implies, the tuff units comprising the aquifer have experienced varying degrees of welding and compaction, causing a great variation in both porosity and permeability. These zones, which are densely welded, have less than five percent porosity, while the nonwelded basal or top portions of individual units may show porosities in excess of 50 percent (Winograd and Thordarson, 1975). Along with welding, the units exhibit a fair degree of columnar jointing and foliation in response to cooling stresses. Thus, although interstitial permeability is small, due to welding, overall permeability is moderate because of jointing and fracturing. Core samples of the Topopah Spring, Tiva Canyon, and Rainier Mesa Tuffs show interstitial porosities ranging from 3 to 48 percent (Winograd and Thordarson, 1975). Saturated hydraulic conductivities calculated from drawdown curves of three pumping wells in the Topopah member in southern Yucca Flat yielded moderate values, ranging from 3.8 to 5.1 m day^{-1}.

Lava Flow Aquifer

The lava flow-tuff aquifer is extremely limited in extent and composed primarily of three formations restricted to the vicinity of Jackass Flats. The permeability and porosity of this

2.4.1.2.2 Groundwater Movement

Winograd and Thordarson (1975) classified groundwater movement within the NTS into three categories: (1) movement of perched water, (2) intrabasin movement, and (3) interbasin movement. The first two categories describe localized groundwater movement within individual basins, while the third is concerned with deep regional flow beneath and through basins.

Occurrence and Movement of Perched Water

Perched water consists of groundwater that has been separated from the underlying zone of saturation by unsaturated conditions, temporarily forming an inverted water table (Freeze and Cherry, 1979). At the NTS, perched groundwater forms principally within the aquitards in the foothills and ridges flanking the basins (namely the bedded tuff and lava flow aquitard) as water travels to the regional water table below. The relatively low permeability of the units compared to those units surrounding them accounts for the existence of perched water, as drainage of water from overlying units is retarded from reaching the water table. Movement from localized perched water is downward.

Thordarson (1965) showed that the occurrence of perched groundwater is erratic rather than widespread. Perched water is not known to occur beneath Yucca Flat, Jackass Flats, or Frenchman Flat.

Intrabasinal Groundwater Movement

The movement of water from the Cenozoic aquifers and aquitards (Figure 2.14) to the underlying Paleozoic units is called intrabasin flow. It is believed that water stored within the Cenozoic aquifers eventually drains into the underlying lava flow and bedded tuff aquitards. Leakage of this water into the underlying carbonate aquifer is restricted because of the low permeability of these units. A description of the processes governing flow through these "leaky systems" is common in the literature (Bear, 1972; and Hantush, 1964). In Yucca Flat and Frenchman Flat, the water in the Cenozoic aquitards behaves as if it were perched above the underlying lower carbonate aquifer. As a result, flow is directed downward (Winograd and Thordarson, 1975). Farther south, in the Amargosa Valley, the direction of water flow is reversed (e.g. flow is upwards, from the carbonate aquifer towards the surface) because of the greater hydraulic head within the carbonate aquifer (Fiero and Maxey, 1970).

SOUTH CENTRAL GREAT BASIN, NEVADA-CALIFORNIA BORDER

Qtal

ALLUVIUM AND COLLUVIUM (QUATERNARY)

Interbasinal Groundwater Movement

Interbasinal flow occurs under confined conditions, e.g. through water-bearing strata that are overlain or underlain by a relatively impermeable layer or aquitard. At the NTS, this refers to flow within the lower carbonate aquifer, confined by the lower clastic aquitard on the bottom, and either the upper clastic aquitard or bedded tuff aquitard above. It is believed that the lower carbonate aquifer and the lower clastic aquifer are hydraulically connected throughout most, if not all, of the NTS (Winograd and Thordarson, 1975). As a result, groundwater flows laterally beneath both mountain ridges and basins, with little regard for the overlying topography. This is what is known as interbasin flow.

Figure 2.14 illustrates the interbasinal flow concept in the saturated zone. Section B-B through Frenchman Flat shows the regional horizontal flow beneath the RWMS in the lower carbonate aquifer. Recharge to the lower aquifer is provided by slow downward leakage from the bedded tuff aquitard, welded tuff aquifer, and valley fill aquifer, and from horizontal movement within the aquifer.

In the NTS, lateral groundwater movement integrates several smaller intermontane valleys into a single basin, referred to as the Ash Meadows groundwater basin (Winograd and Thordarson, 1975; Rush, 1970). This interbasin flow is responsible for the discharge observed at Ash Meadows in the Amargosa Desert, 30 km south of the NTS. This discharge

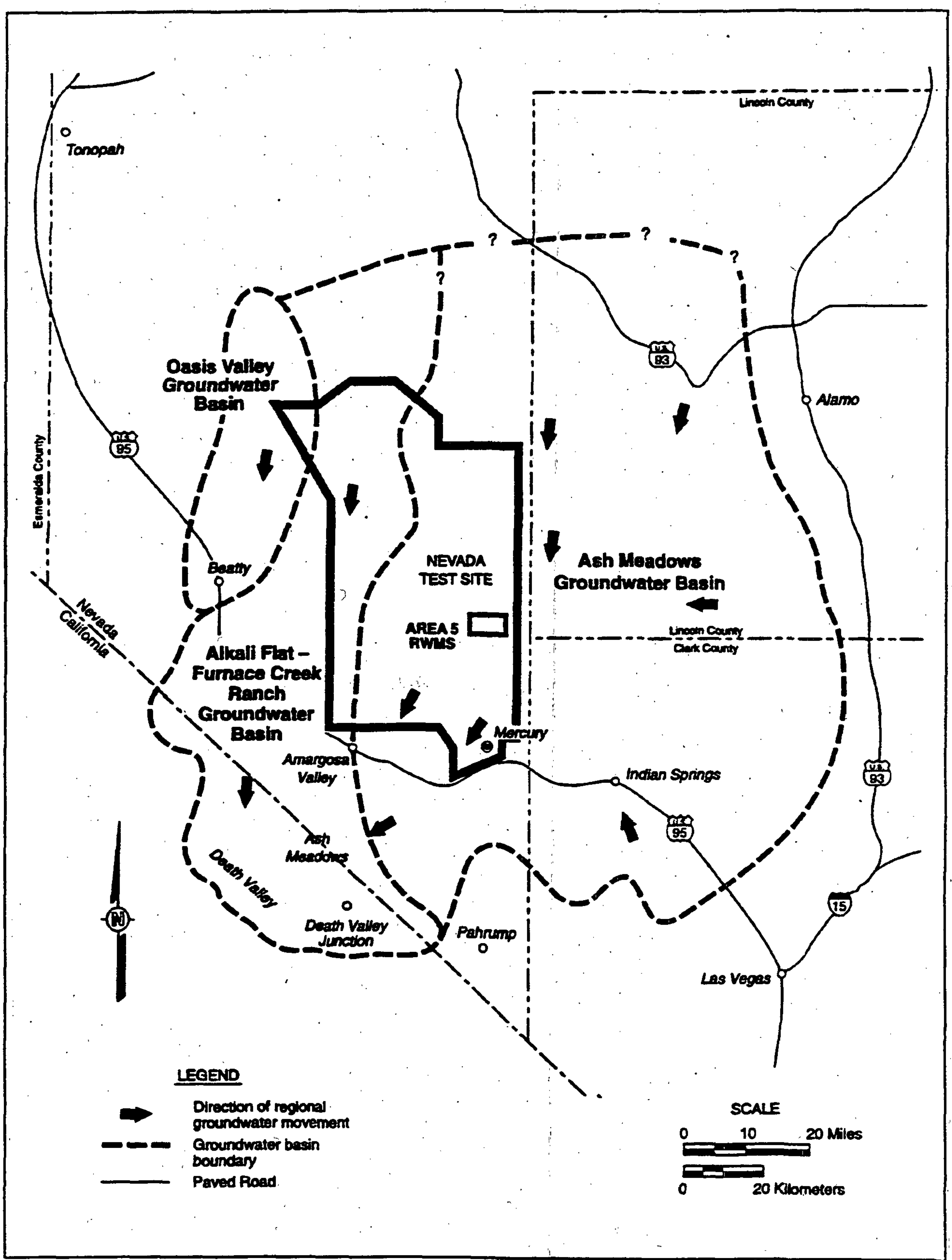
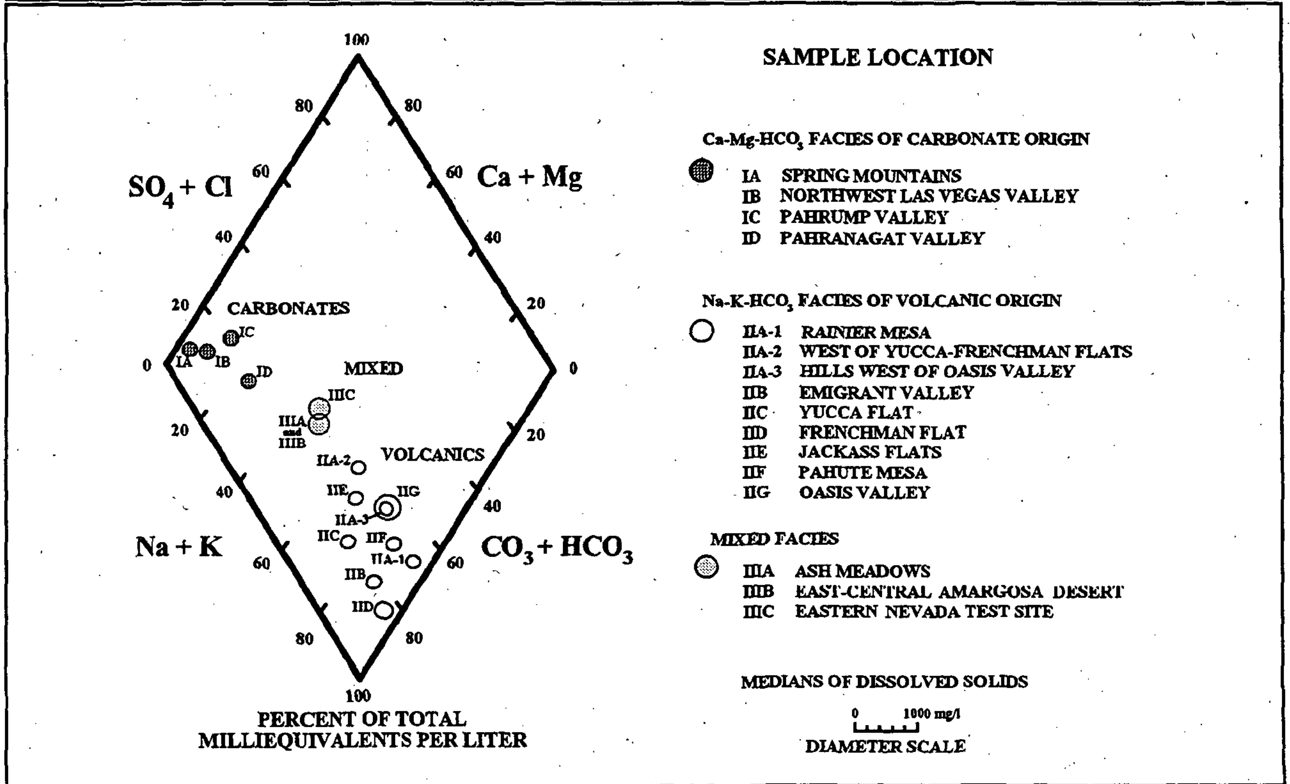


Figure 2.15 - General groundwater flow directions in the NTS area (from Wadell, 1982).

CHEMICAL FACIES OF GROUNDWATER AT THE NTS					
HYDROCHEMICAL FACIES	MEAN CONCENTRATION OF CATIONS AND ANIONS† (milliequivalents l^{-1})				ORIGIN
	Ca+Mg	Na+K	HCO_3+CO_3	SO_4+Cl	
(I) Ca-Mg-HCO_3	4.6	0.7	4.2	1.0	carbonate units
(II) Na-K-HCO_3	1.0	3.6	2.8	1.5	volcanic units
(III) Mixed	3.9	3.8	5.0	2.5	-



†mean values calculated from the average values of each cation and anion for individual valleys within each facies; adapted from Winograd and Thordarson (1975, table 8).

Figure 2.16 - Mean cation and anion concentrations in groundwater found at the NTS and trilinear diagram analysis showing the three dominate chemical facies.

regarding regional groundwater movement. Chemical analyses have been measured from over 150 sources, including wells, springs, and water-bearing fractures.

The groundwater chemistry throughout the study area varies from basin to basin. Schoff and Moore (1964) identified three dominant types: (I) a calcium-magnesium bicarbonate (Ca-Mg-HCO_3) facies within the carbonate units, (II) a sodium and potassium bicarbonate (Na-K-HCO_3) facies derived from groundwater in volcanic rocks, and (III) a mixed facies containing components from both (I) and (II). The facies, their character, and a trilinear analysis of the water chemistry is shown in Figure 2.16.

The Na-K-HCO_3 facies (II) is found within the lava-flow aquifer and tuff aquitard units. The primary source of sodium comes from the alteration of rhyolitic glass containing sodic plagioclase feldspar ($NaAlSi_3O_8$), and from ion exchange with zeolites (Lipman, 1965; Hoover, 1968; and Hem, 1985), which are all major components of the volcanic units at the NTS. The facies is also seen in portions of the valley fill aquifer where a major portion of the alluvial fill material has been derived from the erosion of volcanic units. The Ca-Mg-HCO_3 composition (I) is found within the Paleozoic carbonate units such as the lower carbonate aquifer and in the valley fill aquifers that are composed of carbonate detritus. Most of the calcium and magnesium present is from the dissolution of limestone and dolomite
($CaCO_3$ and $CaMg(CO_3)_2$) mineralization in the unit as it conducts flow. Water of the mixed facies (III) contains portions of both the Na-K and Ca-Mg ions groups. Schoff and Moore (1964) noted that this type of water dominates in the lower carbonate which is between the Amargosa Desert to the south and the eastern border of the NTS.

The Ca-Mg-HCO_3 facies (I) is of major importance in mapping the movement of deep interbasin groundwater flow within the Ash Meadows basin. Schoff and Moore (1964) observed that water in the Ash Meadows discharge area exhibited a chemistry similar to what would occur if water from the volcanics in the valley basins (II) were mixed with water from the deep carbonate aquifer (I), and suggested that groundwater within the NTS is moving southwestward toward Ash Meadows. Winograd and Thordarson (1975) offered further strong contribution of groundwater from the east of the NTS (Chapman and Lyles, 1993), perhaps from diluting recharge waters originating in the Spring Mountains.

The same hydrochemical data suggests a dominance of vertical over lateral flow within

individual basins above the carbonate aquifers, primarily within the volcanic units (Chapman and Lyles, 1993). Winograd and Thordarson observed that interbasin water flowing through the NTS from the northeast to the southwest could originate from the Pahranagat Valley. If this were the case, they reasoned that it was possible to transform those waters (low in sodium and potassium) into those found under the NTS (rich in sodium and potassium), given downward crossflow through the overlying volcanic rock. Further evidence for the dominance of vertical over lateral flow is provided by the increase of sulfate within the mixed facies (III) at Ash Meadows as compared to that found under the NTS. Winograd and Thordarson (1975) observed that the most likely source for the sulfate is the solution of gypsum ($CaSO_4 \bullet 2H_2O$) from tuffaceous sedimentary rocks, claystone, and freshwater limestone of the Pavits Spring and Horse Spring Formations, known to outcrop near Mercury. Such rocks could only be a source if downward crossflow existed.

2.4.2 Hydrology of the Area 5 RWMS

This section describes the hydrology of the Area 5 RWMS. Its emphasis is on the vadose zone and the uppermost aquifer, or valley fill aquifer, since these are the most relevant to the performance of the RWMS.

2.4.2.1 Surface Hydrology

Erosion in Ephemeral Channels Over Geologic Time

The Area 5 RWMS lies on three coalescing alluvial fan systems: the Scarp Canyon and Nye Canyon fan piedmont from the northeast, the southern Halfpint Range and Massachusetts Mountains from the north and northwest, and the Barren Wash fan from the west (Snyder et al. in press). Typical of alluvial fans in an arid climate, the channels on the surfaces of these alluvial fan systems are ephemeral, that is they convey flow only in direct response to runoff-generating storms.

Snyder et al. (in press) evaluated the potential of erosion to expose buried waste at the Area 5 RWMS within the next 10,000 years. They did their evaluation using data collected from previous geomorphic surface mapping and trench and pit wall mapping within and near the Area 5 RWMS (Snyder et al. 1993; Snyder et al. 1994). Snyder et al. (in press) found that the age of the surfaces at the Area 5 RWMS ranged from late Pleistocene (oldest) to late Holocene (youngest), with a predominate surface age from the middle Holocene to late Pleistocene. Late Holocene surfaces are present in the small active channels. In addition, net aggradation has likely occurred at the Area 5 RWMS since at least middle Pleistocene, but evidence of local channel incision and aggradation is present. The maximum depth of a channel incision found near the Area 5 RWMS is less than 1.5 m, with most incisions less than 0.8-m deep. Furthermore, they stated that erosion caused by geomorphic processes is unlikely to reach a depth of 2 m at the Area 5 RWMS within the next 10,000 years. Because of the scarcity of rainfall and the physiographic nature of the RWMS, all available data indicates that channeling to 2.4 m, the depth of buried waste, is possible but extremely unlikely.

Near-Term Flooding Potential at the Area 5 RWMS

In addition to geomorphic studies, a flood assessment was completed to find whether the Area 5 RWMS lies within a 100-year flood hazard area (Schmeltzer et al. 1993). This assessment determines the flood hazard assuming no significant changes in current climatic and hydrologic conditions. Over geologic time (e.g., 10,000 years), climatic and hydrologic conditions could change.

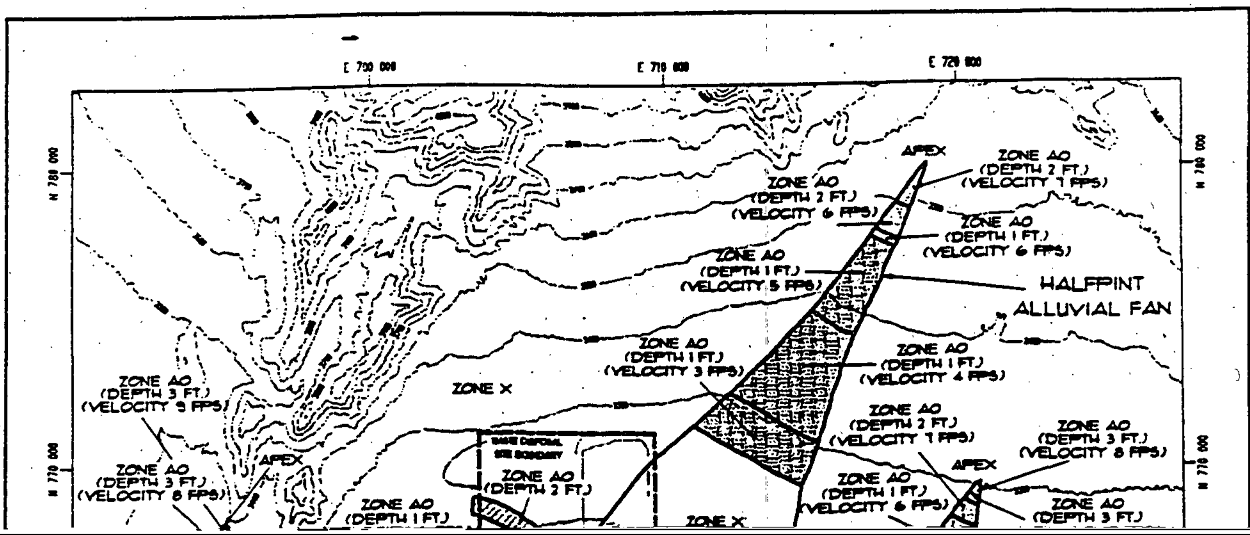
The flood assessment used Federal Emergency Management Agency (FEMA) accepted methods as stipulated in 40 CFR 270.14. Schmeltzer et al. (1993) identified three watersheds that could contribute flooding toward the Area 5 RWMS. These were the Barren Wash, Massachusetts Mountain/Halfpint Range, and Scarp Canyon watersheds. The total drainage area of these three watersheds is approximately 360 km^2. The flood assessment included the Scarp Canyon watershed because the active part of the Scarp Canyon alluvial fan is located within 2 km of the Area 5 RWMS. The Nye Canyon watershed, as identified in Snyder et al. (in press), was excluded because it no longer drains toward the Area 5 RWMS.

A 100-year flood hazard map was delineated using the flood assessment results (Figure 2.17). This map shows that only the southwest corner of the Area 5 RWMS lies within a 100-year flood hazard area, which is defined by FEMA as an area with a 0.01 probability that a flood with a depth of flow greater than 0.3 m can occur in any given year. The southwest corner was impacted by two flood hazards: alluvial fan flooding on the Barren Wash alluvial fan and shallow concentrated flow draining from the Massachusetts Mountains.

The Barren Wash alluvial fan receives flow from the 210-km^2 Barren Wash watershed. As indicated in Figure 2.17, the Area 5 RWMS is located on the lower eastern edge of the 100-year flood hazard area of the Barren Wash alluvial fan and is in a zone designated with a flow depth of 0.3 m and a flow velocity of 0.9 m s^{-1}. One major assumption in the FEMA methodology to evaluate alluvial fan hazards is that flood flow from the apex (e.g., the point where the flow becomes unpredictable) is just as likely to create a new path as it is to follow an existing channel. This means that the probability of a channel passing through any given point on a contour is uniform. Therefore, the 0.3-m depth and 0.9-m s^{-1} designation can be described as the 0.01 probability in any given year that a channel with a depth of 0.3 m or greater and velocities of 0.9 m s^{-1} or greater can occur within this zone.

The second flood hazard area is a result of flow draining from the Massachusetts Mountains and funneling into a shallow, wide channel that crosses the southwest corner of the Area 5 RWMS (Figure 2.17). The average 100-year depth and width of the shallow concentrated flow were approximately 0.6 m and 75 m, respectively. The drainage area contributing to this flood hazard is approximately 16 km^2.

Sheetflow from the 38-km^2 Massachusetts/Halfpint watershed could also affect the Area 5 RWMS. However, flooding as sheetflow was not delineated as a 100-year flood hazard because 100-year depths of sheetflow average less than 0.3 m (Figure 2.17). This flood assessment also determined that a 100-year flood within the 105-km^2 Scarp Canyon watershed will not impact the Area 5 RWMS. The western edge of the 100-year flood hazard on the Scarp Canyon alluvial fan is about 1.2 km east of the Area 5 RWMS.


E 700 000
E 710 000
E 720 000
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APEX
ZONE AO
(DEPTH 2 FT.)
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HALFPINT
ALLUVIAL FAN
ZONE AO
(DEPTH 1 FT.)
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ZONE AO
(DEPTH 1 FT.)
(VELOCITY 4 FPS)
ZONE AO
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ZONE AO
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(DEPTH 3 FT.)

2.4.2.2 Subsurface Hydrology

An idealized conceptual model for the hydrogeologic cross-section of Frenchman Flat and surrounding mountain ridges has been developed based on work done by Case, et. al. (1984), Winograd and Thordarson (1975), Frizzell and Shulters (1990), RSN (1991a, 1991b), and REECo (1993b) (Figure 2.18). The cross-section shown in the figure depicts stratigraphic and structural relations on a gross scale. Downward projection and possible intersections of the faults and bedding contacts with the water table in the subsurface remain uncertain and are highly interpretive.

In spite of the uncertainties, several conclusions can be made. Well cuttings and drill logs from Pilot Wells UE5PW-1, UE5PW-2 and UE5PW-3 (Figure 2.19 and Table 2.4) indicate


EVAPOTRANSPIRATION

The 360 to 460 m thick alluvial unit is assumed to be underlain by approximately 550 m of bedded tuff, which serves as an aquitard. The bedded tuff unit is assumed to be present based on its wide spread occurrence on the NTS and its presence in UE5PW-3. Welded tuff (Ammonia Tanks member of the Timber Mountain Tuff) also was found 180 m beneath the surface in Pilot Well UE5PW-3 (Figure 2.19). Welded tuff was not found to the depth penetrated in Pilot Wells UE5PW-1 and UE5PW-2, thus the extent of the welded tuff unit beneath the RWMS is unknown. Beneath the bedded tuff aquitard lies the lower carbonate aquifer which, in turn, lies above the Precambrian bedrock. The thickness of the carbonate aquifer beneath the RWMS or within the basin itself is unknown.

2.4.2.2.1 Nature of the Vadose Zone

The vadose zone beneath the Area 5 RWMS is the primary barrier between the site and the uppermost aquifer. Three investigations have described the physical, chemical and hydrologic properties of the vadose zone at the Area 5 RWMS. Spatial variation in properties up to a depth of 9 m have been investigated in existing excavations (pits and trenches) at the RWMS (REECo, 1993e). The properties of core and cuttings samples of the near surface vadose zone up to a depth of 37 m has been reported for nine Science Trench Boreholes (REECo, 1993c). The properties of core and cutting samples of the deep vadose zone up to 291 m deep has been described during the Pilot Well study (REECo, 1993b). The location of these wells and trenches are shown in Figure 2.19.

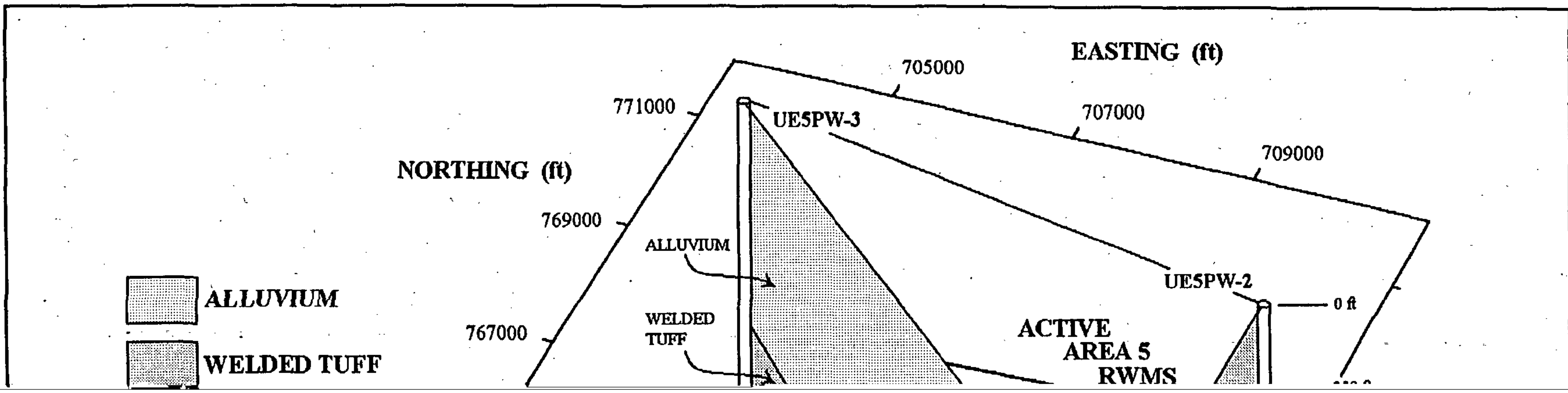
Water Content

The characterization of water content is important for two reasons. First, the degree to which the interstices of a soil are filled with water (water content) has a direct bearing on the comparison of the volumetric water content profiles from the wells and boreholes indicates that the water content throughout the unsaturated zone is remarkably low and uniform, with an overall average of 5.39 percent by weight (8.72 percent by volume). Since the average porosity for the alluvium has been established at about 31 percent, these data show that only 25 percent of the total void space is filled with fluid. This suggests that the pore water is not interconnected and that water flow in the vadose zone is extremely slow.

The lack of variability of water content and water potential with depth suggests that the vadose zone is near steady-state (quasi-steady-state) and probably has not recently undergone significant changes in infiltration. A high degree of uniformity is observed from all three Pilot Wells, with only a very slight increase in water content with depth (Figure 2.20 and Table 2.5.).

Table 2.5. Summary of water content data from the Pilot Wells and Science Trench Borehole studies (REECo, 1993b, 1993c).

VADOSE ZONE WATER CONTENT (θ)



EASTING (ft)
705000
707000
709000
771000
769000
767000
NORTHING (ft)
UE5PW-3
UE5PW-2
0 ft
ALLUVIUM
WELDED TUFF
ALLUVIUM
WELDED TUFF
ACTIVE
AREA 5
RWMS

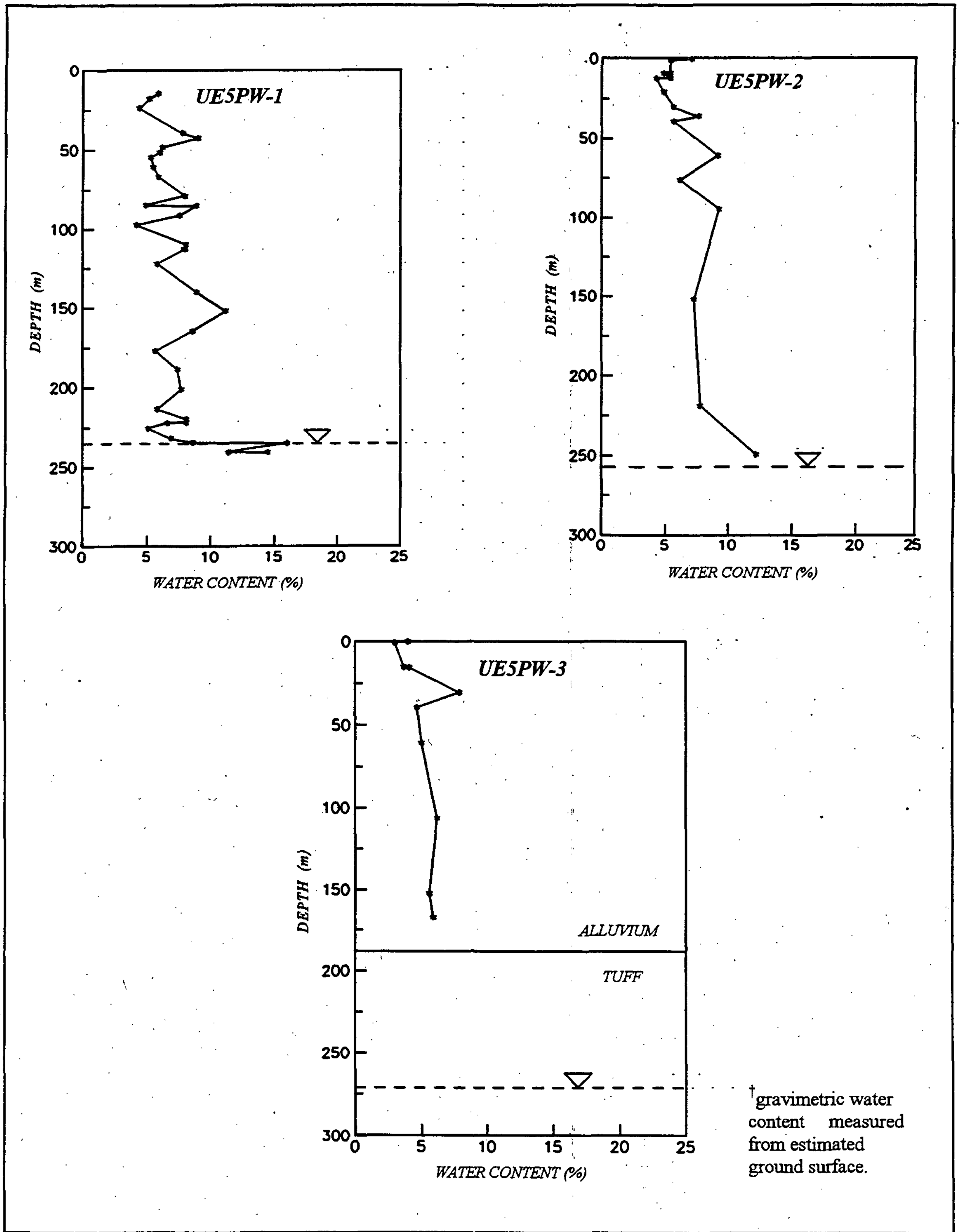


Figure 2.20 - Water content profile beneath Area 5 RWMS based on the Pilot Well data (REECo, 1993b).

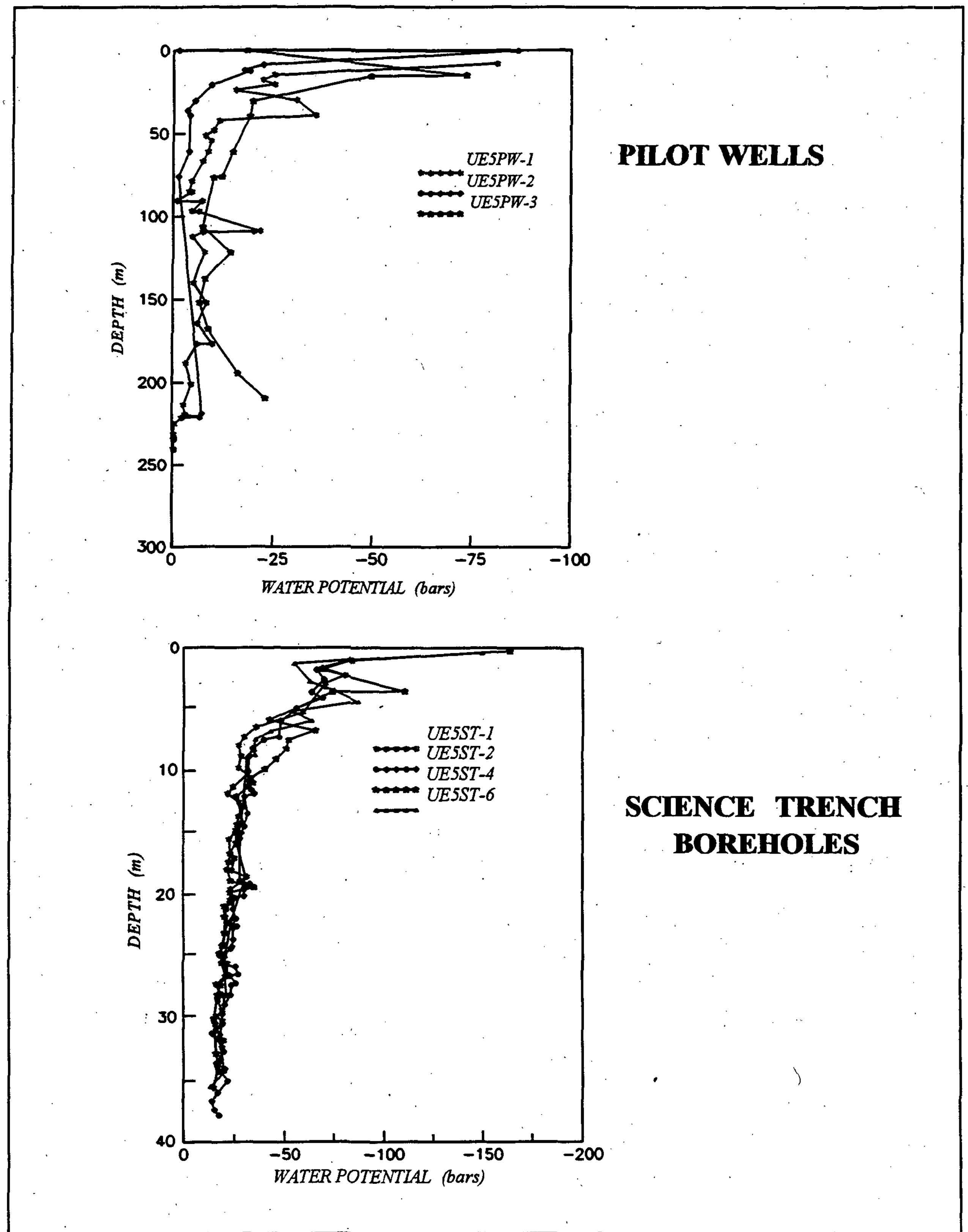


Figure 2.21 - Water potential profiles for the Pilot Wells and Science Trench Boreholes surrounding the Area 5 RWMS (REECo. 1993b. 1993c).

The average magnitude and direction of the total hydraulic potential gradient from point to point within the profile strongly suggests that flow in the vadose zone beneath the Area 5 RWMS is one-dimensional and can be divided into three zones:

- Zone I: An upper zone, approximately 35 m in depth, where a large negative hydraulic potential (driven by evapotranspiration at the surface) creates a potential for upward liquid flow and drying at the near-surface.

- Zone II: An intermediate zone, from 35 m below the surface down to 150 to 220 m, where the hydraulic potential is dominated by gravity drainage causing downward flow. The high values of water potential and low water content suggest that flow is under a quasi-steady-state condition. This condition presumably was reached a considerable time after the end of a much wetter climatic period when recharge was higher.

- Zone III: A lower zone, up to 10 to 20 m above the water table, where the hydraulic potential is near zero and the water is under a capillary fringe condition with relatively static conditions producing little flow.

These three flow regions within the vadose zone are most pronounced in the water potential ($d\psi/dz$) profile for Pilot Well UE5PW-1 which has been smoothed and is represented schematically in Figure 2.22.

It is assumed that water potential is equivalent to matric potential in this plot (O'Neill et al., 1993). The straight line indicates where the gradient of total potential (dH/dz) is zero, e.g. the matric potential driving force is equal and opposite to the gravity potential ($d\psi/dz = -dz/dz$). Values of matric potential that plot to the right of the line occur within Zone I, where the matric potential ($d\psi/dz$) is greater than the potential for gravity drainage ($d\psi/dz > dz/dz$), indicating that the potential for flow is upward. Presumably, this area of upward flow is driven by high evapotranspiration at the surface. The data gathered from the Science Trench Boreholes (Figure 2.21) shows the strongest positive upward gradient is

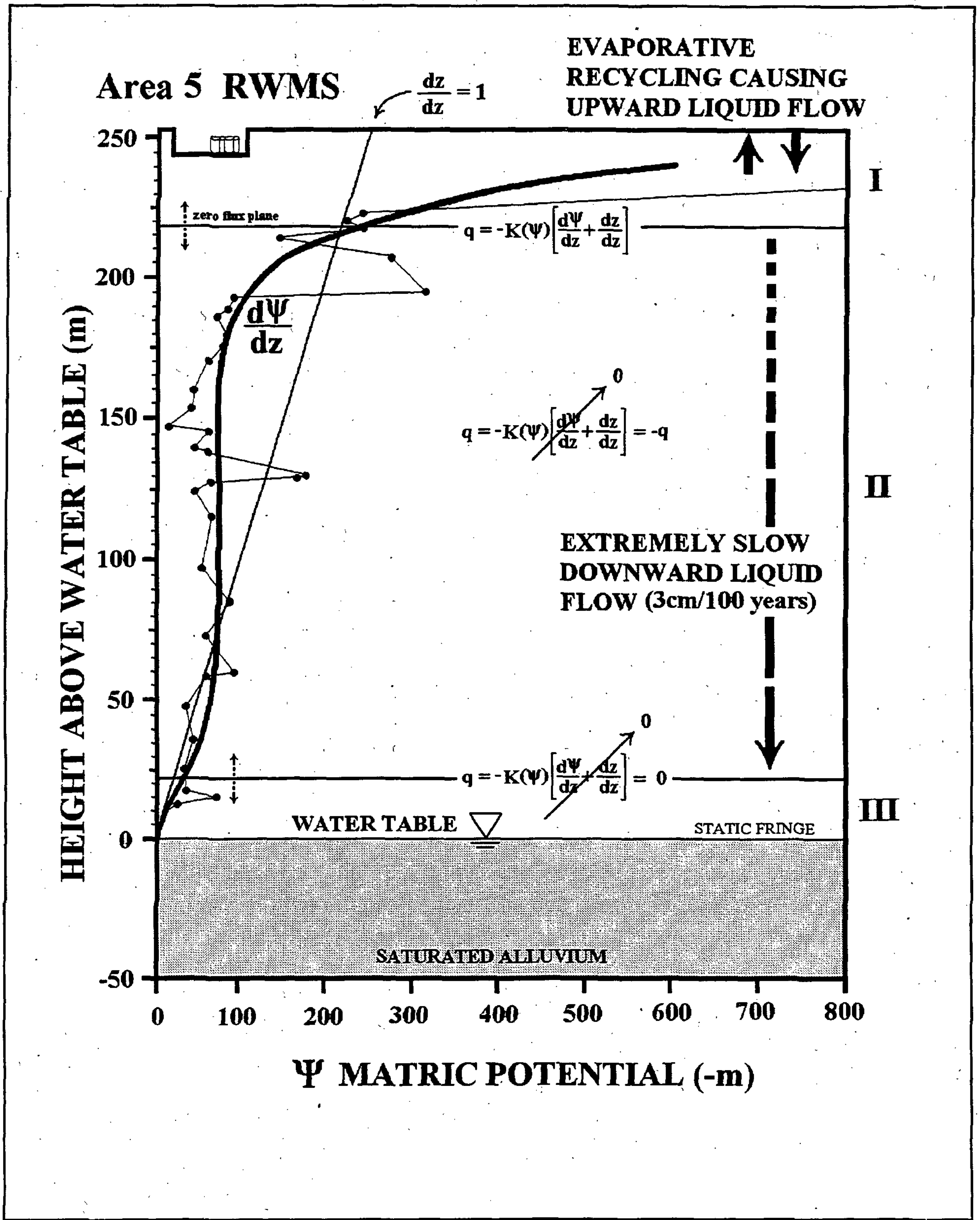


Figure 2.22 - Smoothed matric potential profile for Pilot Well UE5PW-1 illustrating the conceptual model containing three zones of unsaturated flow behavior within the vadose zone in the alluvium under the Area 5 RWMS.

Saturated Hydraulic Conductivity

The saturated hydraulic conductivities (K_{sat}) for 196 undisturbed cores from Pilot Wells UE5PW-1 and UE5PW-2, and five Science Trench Boreholes were determined in the laboratory by REECo (1993b, 1993c), using a constant-head permeameter. These data were analyzed by Sully et al. (1993). The range of values of hydraulic conductivity, over both the Pilot Wells and Science Trench Boreholes, varied by about 3.5 orders of magnitude, from 0.0012 to 5.01 m day^{-1}, with mean values ranging from 0.36 to 4.9 m day^{-1} (Figure 2.23). These values are similar to those presented for alluvium in the region by Winograd and Thordarson (1975) in Table 2.3.

Statistical analyses were carried out by Sully et al. (1993) and Istok et al. (1994) to quantify the degree of anisotropy within the alluvium for saturated hydraulic conductivity. The K_{sat} for the alluvium was found to be lognormally distributed, as was observed by Jury et al. (1987) for many other soils in numerous field studies. The spatial structure of the saturated hydraulic conductivity was determined using empirical variograms. No evidence was found for the existence of vertical anisotropy in the upper 37 m of alluvium. Thus, despite the visual evidence of layering within the alluvium, the material behaves as a homogeneous mass

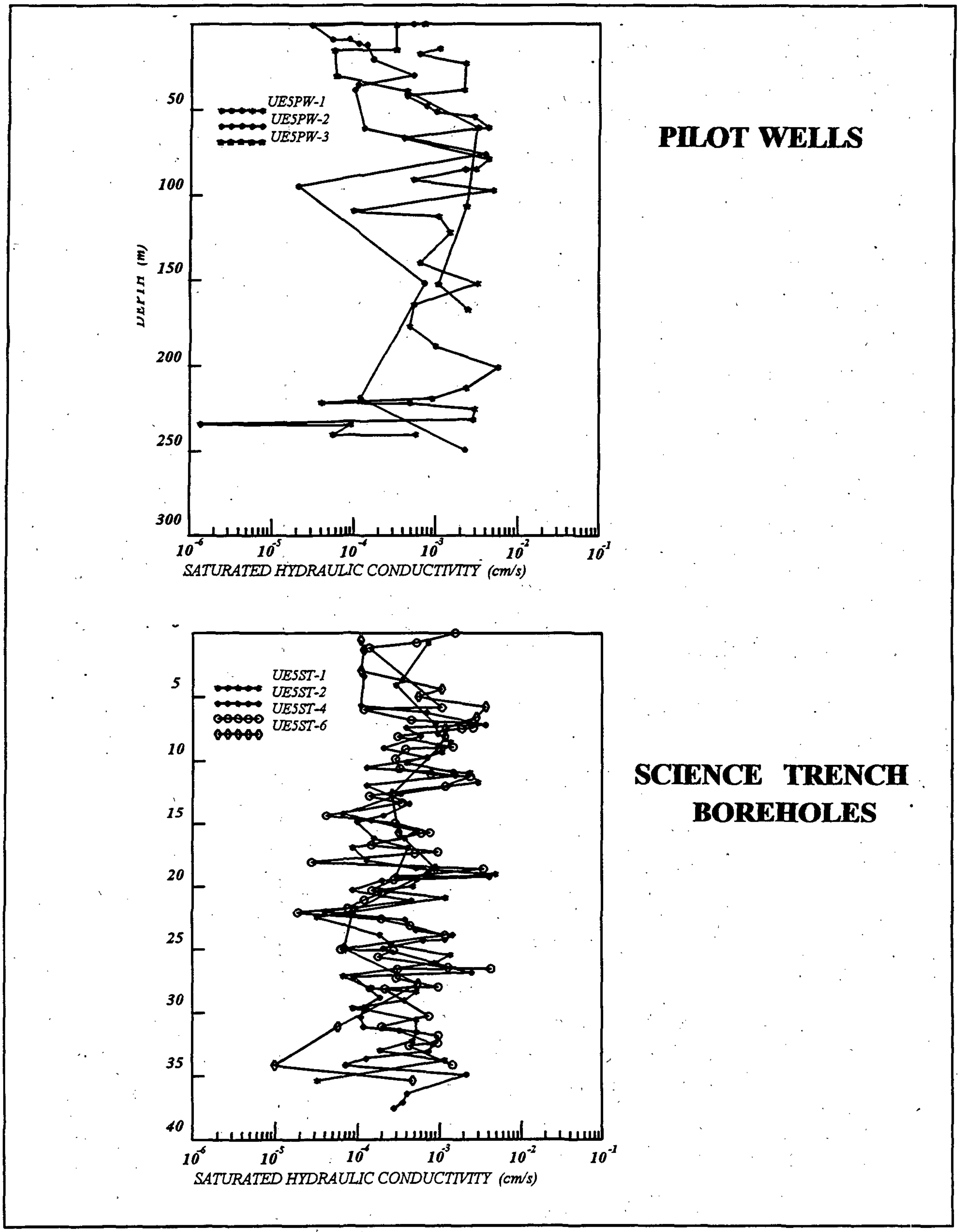


Figure 2.23 - Saturated hydraulic conductivity profiles for the Pilot Wells and Science Trench Boreholes surrounding the Area 5 RWMS (REECo, 1993b, 1993c).

the moisture retention curves for each Pilot Well are shown in Figure 2.24. Each set of curves for a given Pilot Well reflects the entire sampling depth, e.g. samples taken at different depths are pooled. The general shape of the curves denote a sandy or coarse-grained deposit with a large variation in pore-size distribution (Hillel, 1980). Similar curves, using the cores from the Science Trench Boreholes and existing pit excavations, can be found in REECo (1993c, 1993e). The remarkable similarity between all the curves for the various sampling depths and locations near the Area 5 RWMS lends further support to the hypothesis of gross homogeneity of the hydrologic character of the alluvium.

The moisture-retention function, $\psi(\theta)$, was first determined by fitting the moisture retention data (Figure 2.24) to the derivation of water content by van Genuchten (1978, 1980):

$$\theta_V = \theta_r + (\theta_s - \theta_r)\left[1 + (-\alpha\psi)^n\right]^{-m} \tag{2.1}$$

where θ_v is the volumetric water content (cm^3 cm^{-3}), θ_s is the saturated volumetric water content, θ_r is the residual volumetric water content, ψ is the matric potential (cm), and α, m, and n are empirically determined parameters. This yielded smooth moisture retention functions, $\psi(\theta)$, which were used to derive the unsaturated hydraulic conductivity curves. These final unsaturated hydraulic conductivity curves (K(θ)) were derived by substitution of the van Genuchten moisture retention curve-fitting parameters into the Maulum (1976) model for unsaturated hydraulic conductivity to obtain:

$$K(\theta) = K_s S^{1/2}\left[1 - \left(1 - S^{1/m}\right)^m\right]^2 \tag{2.2}$$

where K_s is the saturated hydraulic conductivity and S is the effective saturation as defined by:

$$S = \frac{(\theta_v - \theta_r)}{(\theta_s - \theta_r)} \tag{2.3}$$

The unsaturated hydraulic conductivity functions (K(θ)) from Equation (2.2) for the three Pilot Wells are presented in Figure 2.25. At the mean water content for the alluvium (7 to 12 percent), the magnitude of K(θ) is only about 8.6×10^{-8} m day^{-1} (1.0×10^{-10} cm s^{-1}). The magnitude of liquid flow under such low hydraulic conductivities is negligible. Pore water under such circumstances is essentially immobile. These data argue that liquid flow at the low water contents currently present within the alluvium is highly unlikely.

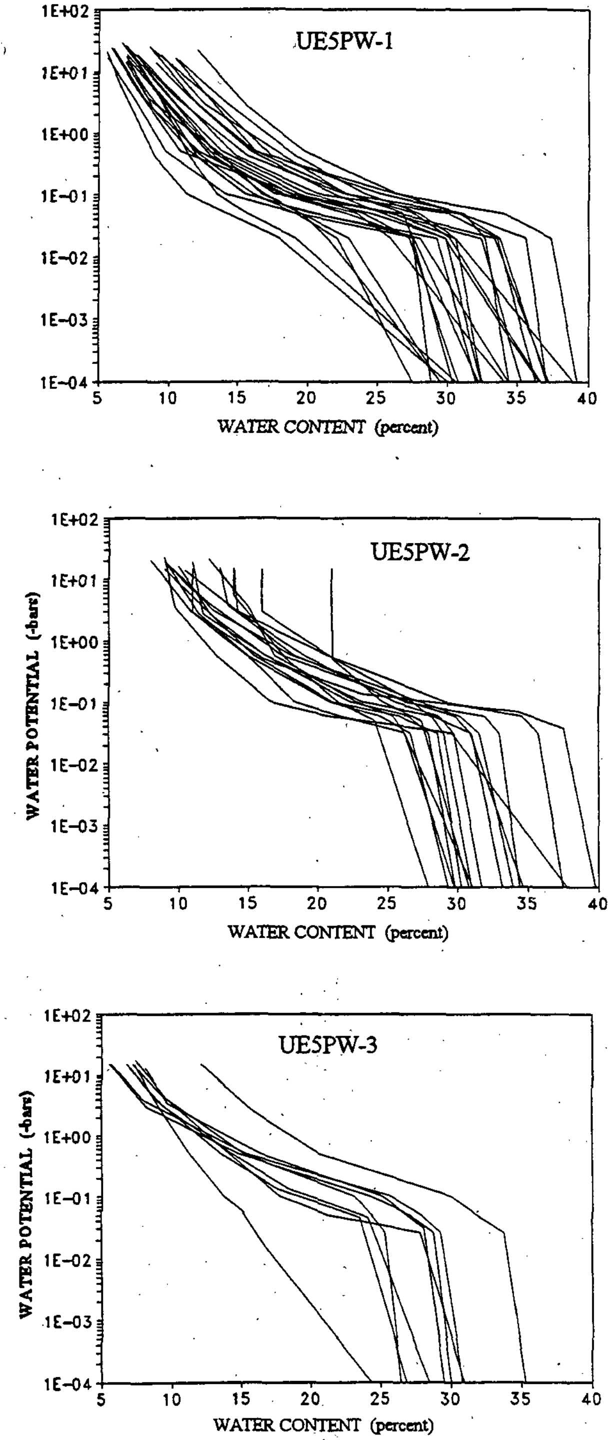


Figure 2.24 - Composite moisture retention characteristic curves from core samples for the Pilot Wells UE5PW-1, UE5PW-2, and UE5PW-3, (REECo, 1993b, 1993c).

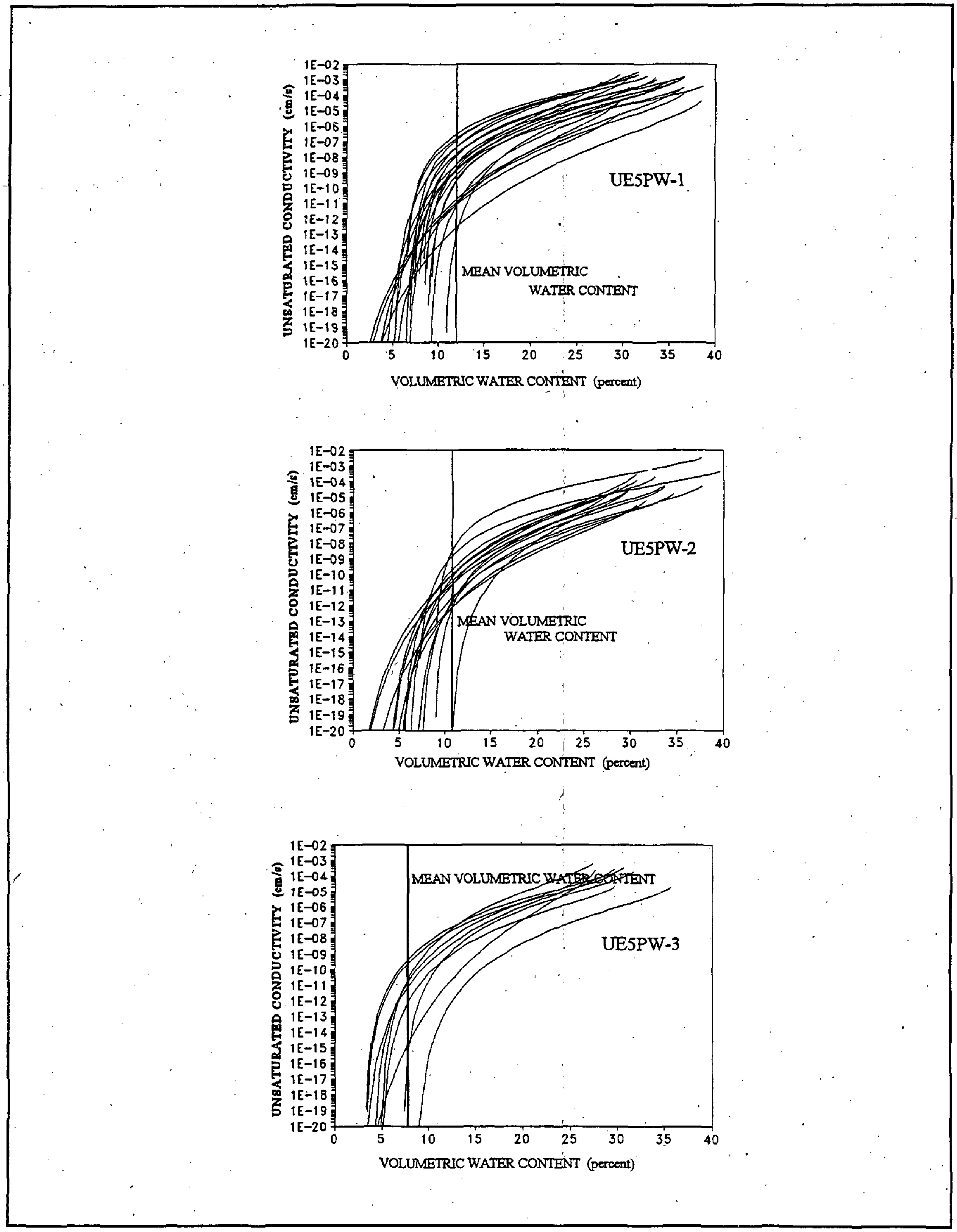


Figure 2.25 - Fitted unsaturated hydraulic conductivity functions from core samples in Pilot Wells UE5PW-1, UE5PW-2, and UE5PW-3 (REECo, 1993b).

2.4.2.2.2 Environmental Tracers in the Vadose Zone

The concentrations of certain ions, as well as those of stable isotopes of certain elements, can serve as environmental tracers. These tracers can be used to estimate vadose zone water movement, travel times, and recharge, independently of a hydraulic analysis. REECo (1993b) measured profiles for chloride (Cl), stable oxygen (^{18}O), and stable deuterium (^{2}H) in both the Pilot Wells and Science Trench Boreholes surrounding the RWMS. The environmental tracer data support the hypothesis that evaporation is the dominant process governing the rate and direction of water movement within the upper vadose zone under the present arid climate. Downward infiltration is not indicated by the environmental tracer data.

Chloride Profiles

Chloride anions can be viewed as a conservative tracer within the NTS; it is neither generated nor decomposed within the soil zone. A difference between long-term input and output indicates increasing or decreasing salinity, representing soil water flux. This technique is known as the chloride mass balance method (Allison and Hughes, 1983).

Chloride concentrations were reported for both drill cuttings and core samples from the Pilot Wells and Science Trench Boreholes (REECo, 1993b, 1993c). These depth profiles, presented in Figure 2.26, show relatively high accumulations of chloride in the shallow subsurface of all the boreholes, suggesting that evaporation rates are high compared to downward movement of water. If downward flow were an important process at the RWMS, chloride concentrations in soil water beneath the root zone would be much lower than those observed in the three Pilot Wells.

Stable Isotope Profiles

The stable isotopes of hydrogen and oxygen provide an excellent record of water movement in the subsurface because they are components of the water molecule itself. Three stable isotopes of oxygen (^{16}O, ^{17}O, ^{18}O) and two stable isotopes of hydrogen (^{1}H, ^{2}H or deuterium, denoted D) exist in nature, thus water molecules in precipitation have nine possible isotopic configurations and masses. Each configuration will exhibit a slightly different vapor pressure, as the vapor pressure of any given molecule is inversely proportional to its mass.

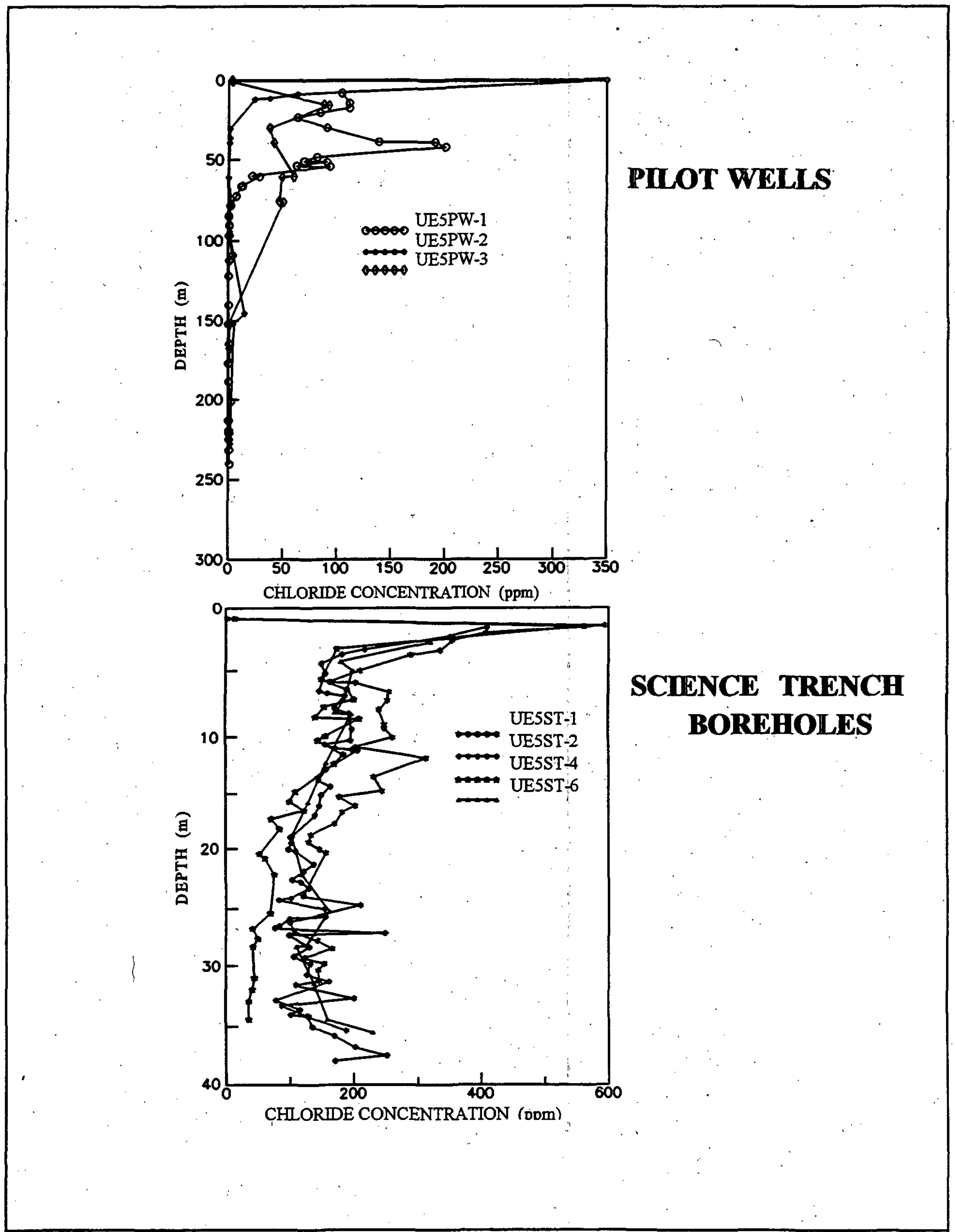


Figure 2.26 - Depth profiles of dry chloride concentrations for core samples from the Pilot Wells and Science Trench Boreholes (REECo, 1993b, 1993c).

This implies that fractionation between the heavier molecules and lighter molecules of water can occur during evaporation and precipitation. Isotopic ratios are reported as differences of $^{18}O/^{16}O$ and D/H ratios, relative to Standard Mean Ocean Water (SMOW) first defined by Craig (1961a) with reference to a large volume of distilled water distributed by the National Bureau of Standards in the United States. Samples of water are compared by their isotopic compositions of oxygen and hydrogen, expressed as a per mil difference relative to SMOW:

$$\delta\, ^{18}O = \left[\frac{(^{18}O/^{16}O_{SAMPLE}) - (^{18}O/^{16}O_{SMOW})}{(^{18}O/^{16}O_{SMOW})} \right] X\ 1000 \qquad (2.4)$$

$$\delta D = \left[\frac{(D/H)_{SAMPLE} - (D/H)_{SMOW}}{(D/H)_{SMOW}} \right] X\ 1000 \qquad (2.5)$$

Consequently, positive values of $\delta^{18}O$ and δD reflect enrichment in the heavier isotopes of oxygen and hydrogen, and negative values indicate depletion relative to the SMOW standard.

Once precipitation enters the soil horizon, water in the liquid phase is enriched in ^{18}O and D because evaporation favors the removal of lighter isotopes. Likewise, the liquid phase is enriched in heavy isotopes by condensation of water vapor.

The continuing preferential removal or fractionation of lighter isotopes from the emplaced water caused by both evaporation and condensation should be recorded in pore water as positive (less negative) values compared to the SMOW standard and nearby water at depth. This is exactly what is seen in the stable oxygen/hydrogen profiles for the three Pilot Wells and Science Trench Boreholes shown in Figure 2.27. In general, the $\delta^{18}O$ and δD profiles show greater enrichment of the heavy isotopes in the upper vadose zone (top 30 m), suggesting that the shallow vadose zone water has been subjected to more evaporation/condensation cycles than the deeper water. Using the SMOW reference, a line representing the average ratios of $^{18}O/^{16}O$ and D/H for waters sampled throughout the world, known as the Meteoric Water Line (MWL), has been prepared by Craig (1961a) as

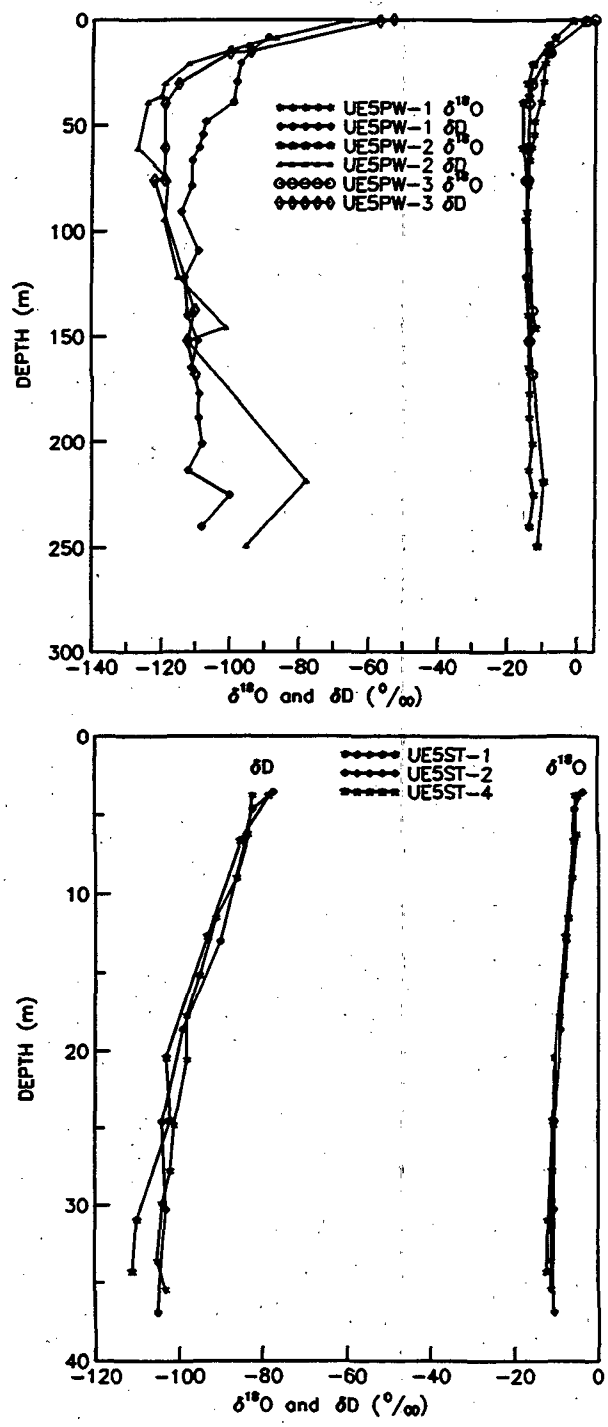


Figure 2.27 - Depth profiles of б^{18}O and бD from core samples from the Pilot Wells and Science Trench Boreholes (REECo 1993b, 1993c).

shown in Figure 2.28. The MWL shows that the δ^{18}O and δD values of meteoric water can be represented by the equation:

$$\delta D = 8\,\delta^{18}O + 10 \tag{2.6}$$

The importance of the MWL is its use in comparing samples of water as an indication of their origin and climate of formation (Merlivat and Jouzel, 1979; Jouzel and Merlivat, 1984; Jouzel et al., 1991; Stewart, 1975; and Gat and Dansgaard, 1972).

Figure 2.28 compares δ^{18}O versus δD for the three Pilot Wells and the global MWL. The stable isotope lines for the three Pilot Wells lie to the right of the global MWL indicating that the waters have been subjected to evaporation over time (Domenico and Schwartz, 1990). These data and figures support the hypothesis that evaporation at the Area 5 RWMS is the dominant hydrologic mechanism in the upper vadose zone compared to downward liquid flow under the present climate.

2.4.2.2.3 Summary of Vadose Zone Characterization Data

In summary, the following conclusions for the vadose zone can be drawn from the site characterization data:

- The alluvium may be considered homogeneous with respect to particle size distribution with depth on a gross scale and is characterized as a well-graded medium sand with gravel and a small amount of fines.

- The hydrologic properties of the alluvium are homogeneous and isotropic. This includes porosity (n), saturated hydraulic conductivity (K_{sat}), moisture retention ($\psi(\theta)$), and unsaturated hydraulic conductivity ($K(\psi)$) (Sully et al. 1993; Istok et al. 1994). For the purposes of hydrologic modeling the alluvium penetrated by the Pilot Wells and Science Trench Boreholes can be assumed to be a single homogeneous and isotropic lithological unit.

- Water content of the alluvium is very low near the surface and increases only slightly with depth (from 5 percent at the surface to about 10 percent at a depth of 37 m). This indicates that the entire vadose zone is very dry.

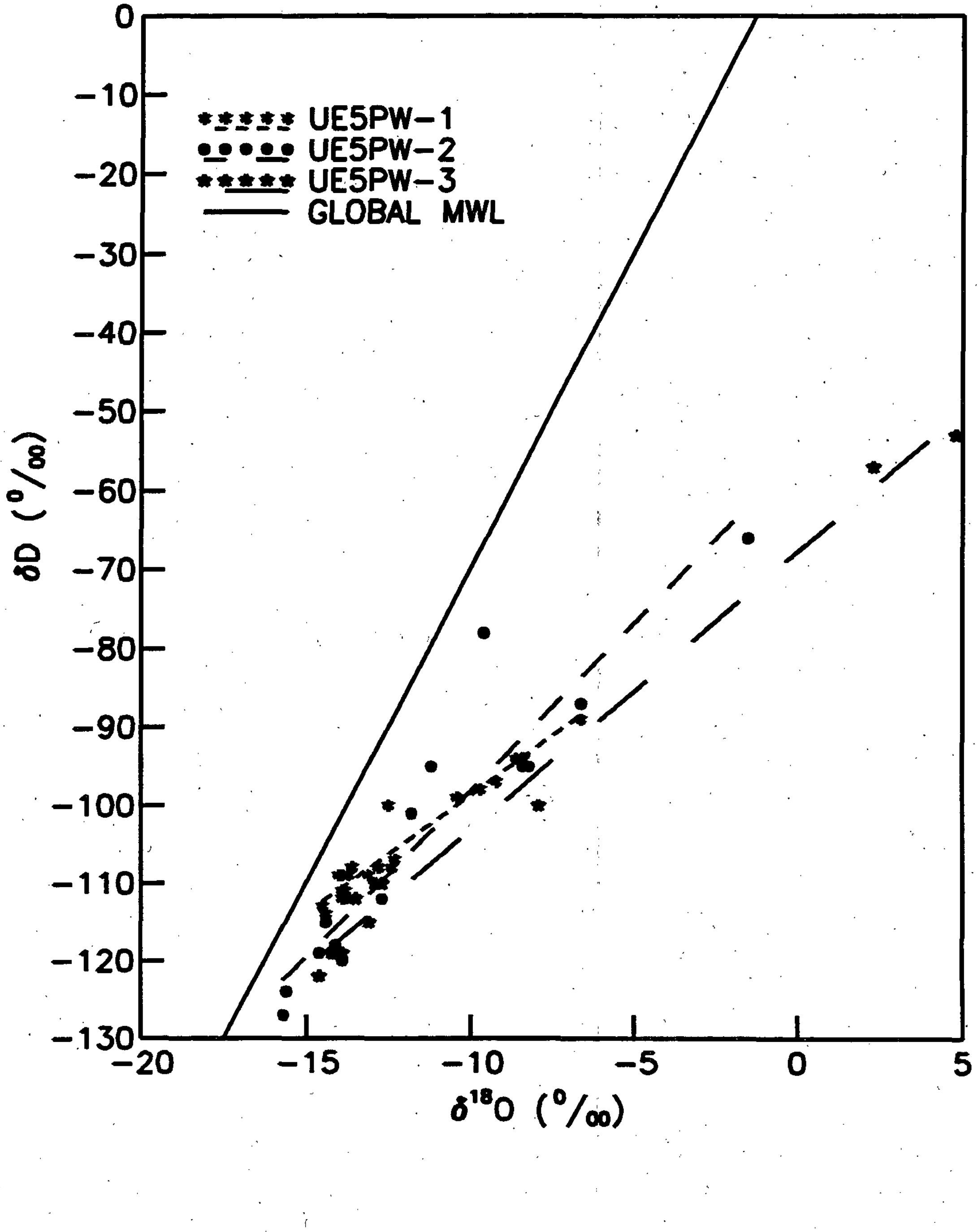


Figure 2.28 - Comparison of stable isotopes measured from core samples of the Pilot Wells

- Water potential measurements (ψ, a measure of the strength of the driving force causing fluid flow) show a large negative gradient in the upper portion of the alluvium (indicating a tendency for water to flow upward to the surface) because of high evapotranspiration at the land surface. The upward potential exists throughout the upper 35 m of alluvium, with the largest upward gradient in the upper 9 m.

- Very little if any liquid flow is occurring within the upper 35 m of the vadose zone because the unsaturated hydraulic conductivity values ($K(\psi)$) are so small, due to the very low water content of the alluvium.

- Depth profiles show an enrichment near the surface of stable chloride and bromide, as well as the heavier naturally occurring isotopes of hydrogen and oxygen. This provides strong evidence that evaporation is the dominant hydrologic process in the upper vadose zone. Water that exists deeper in the vadose zone probably entered the system under a much wetter climate.

These data suggest that the small amount of liquid water infiltrating at the surface during infrequent rainfall events (diffuse recharge) does not migrate down to the water table (REECo, 1993a; Ginanni et al., 1993; O'Neill et al., 1993; and Detty et al., 1993), but rather west of the Area 5 RWMS (Fouty, 1989). Using the chloride mass balance technique, Fouty (1989) estimated the recharge rate and concluded that drainage below 10 m was minimal or nonexistent for at least the last 6,000 years. The conclusion drawn from the stable isotope data is that the current climatic regime, reflected by the enrichment in the near surface by various stable isotopes, has existed for a very long time and that under this regime, contaminant transport and flow in the liquid phase can be considered minimal.

2.4.2.2.4 Estimation of Unsaturated Flow Rate and Direction

In the previous sections it was shown that infiltrating precipitation at the Area 5 RWMS does not recharge the aquifer, but is rapidly recycled to the atmosphere. The thickness and low water content of the vadose zone offers an additional protection against contamination of the uppermost aquifer. In the unlikely event that leachate were to reach Zone II, were drainage and Darcy's law for vertical unsaturated flow becomes:

$$q_z = -K(\theta)\left[\frac{d\psi}{dz} + 1\right] \tag{2.9}$$

An order of magnitude estimate of the average rate of downward water movement through Zone II (35 to 150 m below the land surface) can be calculated using the total water potential data and unsaturated hydraulic conductivity relations gathered from the Pilot Wells and Science Trench Boreholes (shown in Figures 2.21 and 2.25).

The largest mean volumetric water content observed within the three Pilot Wells was 11.1 percent, occurring in UE5PW-1 (REECo, 1993b). From Figure 2.25, the unsaturated hydraulic conductivity, calculated at 11.1 percent volumetric water content, ranged from about 5×10^{-6} to 5×10^{-12} cm s^{-1}, with a mean of about 1×10^{-9} cm s^{-1}. Since Figure 2.22 indicates that the matric potential in Zone II of the vadose zone is zero ($d\psi/dz = 0$), the magnitude of flux in Equation 2.9 is equal to the unsaturated hydraulic conductivity ($q = K(\theta)$) or 1×10^{-9} cm s^{-1}. The actual flow is limited to the water-filled pore space and does not occur through the entire cross-section. Given an average water filled porosity (n_w) of 10 percent, the mean pore velocity (v) can then be calculated as $v = q/n_w$, or about 3 mm yr^{-1}. These calculations show that it would take approximately 64,500 years for liquid to travel from the top of Zone II to the water table, approximately 245 m below the RWMS, under the current hydrologic conditions. Site characterization data strongly supports the conclusion that recharge of the aquifer is not occurring at the Area 5 RWMS. However, if it were to occur, the long travel time through the vadose zone would allow most radionuclides to decay to negligible levels before reaching the aquifer.

2.4.2.2.5 Saturated Flow Within the Uppermost Aquifer and Aquitard

Saturated flow occurs in the lowermost portions of the valley fill aquifer and the bedded tuff aquitard (Figures 2.13 and 2.14) below the vadose zone and water table. Flow in the saturated portion of Frenchman Flat was characterized by Winograd and Thordarson (1975) as intrabasinal flow, e.g. groundwater movement was hypothesized to be primarily downward from the alluvium into the underlying aquitards, eventually draining into the lower carbonate aquifer. Evidence that recharge through the vadose zone under the present climatic conditions is extremely small has already been presented along with additional evidence that the travel time through the vadose zone is extremely long. Thus, the chances of radioactive contamination entering the saturated zone via liquid transport are minimal. It can further be shown that if contamination were to reach the aquifer, movement in the saturated zone would also be extremely slow.

For two-dimensional saturated flow in the x-z plane, the flux can be described by Darcy's law, in tensor form:

$$\underline{q} = -\boldsymbol{K}\cdot\nabla H$$

$$\text{or...} \quad \begin{bmatrix} q_x \\ q_z \end{bmatrix} = -\begin{bmatrix} K_{xx} & K_{xz} \\ K_{zx} & K_{zz} \end{bmatrix} \begin{bmatrix} \dfrac{\partial H}{\partial x} \\ \dfrac{\partial H}{\partial z} \end{bmatrix} \tag{2.10}$$

where q is the vector defining the horizonal (q_x) and vertical (q_z) components of flow, **K** is the conductivity tensor, and ∇H represents the vector containing the horizontal (∂H/∂x) and vertical (∂H/∂z) gradients. Since the analyses by REECo (1993b, 1993c) suggest that the hydraulic conductivity of the alluvium in the vadose zone appears grossly homogeneous ($K_{xx}=K_{zz}$) and isotropic ($K_{xz}=K_{zx}=0$), it is reasonable to assume that the character extends into the saturated zone as well. With these assumptions Equation 2.10 can be rewritten as:

$$\begin{bmatrix} q_x \\ q_z \end{bmatrix} = -\begin{bmatrix} K_{sat} & 0 \\ 0 & K_{sat} \end{bmatrix} \begin{bmatrix} \dfrac{\partial H}{\partial x} \\ \dfrac{\partial H}{\partial z} \end{bmatrix} \tag{2.11}$$

Thus, the horizontal and vertical components of flow can be described by two equations, one for the horizontal component (q_x), and one for the vertical (q_z):

$$\begin{aligned} q_x &= -K_{sat}\frac{\partial H}{\partial x} \\ q_z &= -K_{sat}\frac{\partial H}{\partial z} \end{aligned} \tag{2.12}$$

which can be added as vectors to yield the total magnitude and direction of flow within the saturated portions of an isotropic hydrological unit such as the valley fill aquifer.

Vertical Saturated Flow

There has been no systematic evaluation of the vertical component of the hydraulic gradient in Frenchman Flat. Winograd and Thordarson (1975) concluded that a generalized vertical flow was more likely than a horizontal flow through the uppermost unconfined Cenozoic units. Downward leakage is more likely than horizontal flow because: (1) the water levels in the Cenozoic strata in surrounding valleys were comparable to those observed in Frenchman Flat, indicating an absence of horizontal gradient; (2) water levels in wells tapping the lower carbonate aquifer, two along the north and east peripheries of the basin and one on the southwestern edge, show a piezometric surface somewhat lower (3 to 10 m) than that in the Cenozoic units, indicating a possible downward vertical gradient; and (3) the lower carbonate aquifer rises on the edge of the basin (except the west) so that any recharge within the basin, even horizontal, must eventually drain into it. Nevertheless, Winograd and Thordarson also recognized that recharge to the lower carbonate aquifer from overlying units beneath the valley floors in the NTS seemed improbable under the present climatic conditions, e.g. that vertical seepage through the valley floors was a distant second to recharge from precipitation directly onto the carbonate aquifer, especially in areas of high elevation and rainfall.

The consensus opinion, reached prior to obtaining the vadose zone site characterization data previously presented, was that at least some degree of vertical flow and recharge into the lower units from the Cenozoic units occurred through the valley floors. However, there is no hard evidence for substantial vertical movement in the uppermost aquifer units within the basins of the NTS. Even the minimal vertical flow proposed by Winograd and Thordarson (1975) could, due to mass balance considerations, only exist if vertical recharge first occurs. Evidence that no such recharge occurs has been presented. This is a strong argument against the existence of any significant amount of vertical flow within the Cenozoic units beneath the Frenchman Flat. Also, the existence of vertical flow would imply a declining water table. No evidence of such a decline exists. If vertical flow does indeed occur, it is probably restricted to areas of higher precipitation (e.g. near mountain slopes and peaks surrounding NTS basins where recharge is directly into the Cenozoic units). Some degree of vertical flow may also exist on the margins of the basins, but this is probably minimal within the interior of Frenchman Flat.

The extent of vertical flow beneath the Area 5 RWMS could be ascertained by a comparison of the potentiometric head in the lower units below the RWMS to that found in the saturated Cenozoic aquifer, e.g. to measure the vertical hydraulic gradient. The data required for this comparison are not available. However, a rough approximation of the vertical hydraulic gradient can be estimated from data obtained from existing wells if the following assumptions are made:

1. The top of the upper surface of the lower carbonate unit is approximately 1,340 m below the land surface, and the average depth to the water table is about 250 m, yielding a saturated thickness above the carbonates of (1,340-250) = 1,090 m. (Figures 2.10, 2.14, and Table 2.4).

2. The saturated thickness beneath the Area 5 RWMS is primarily composed of the bedded tuff aquitard (Figures 2.18 and 2.19).

3. For purposes of analysis, the tuff can be considered to be anisotropic but homogeneous, e.g. the vertical hydraulic conductivity is constant in space.

4. The maximum difference between potentiometric surfaces for the lower carbonate aquifer and the upper saturated valley fill aquifer cited by Winograd and Thordarson (1975) within Frenchman Flat applies beneath the RWMS and is about 10 m.

Accordingly, the magnitude of the vertical hydraulic gradient (dH/dz) is 10/1,090 = 0.009174 m m^{-1}. Based on one-dimensional flow theory, Darcy's law can be used to determine the mean pore flow velocity (v) within the bedded tuff aquitard. Given an average water-filled porosity (n_w) of 37.7 percent, and the saturated hydraulic conductivity (K_{sat}) of 0.006 m day^{-1} (Table 2.3), the estimated vertical mean pore flow velocity is:

$$v = \frac{q}{n_w} = \frac{K_{sat}}{n_w}\frac{dH}{dz} = \frac{0.006 m/day}{0.377} \cdot 0.009174 \; \frac{365 day}{yr} = 0.053 m/yr \qquad (2.13)$$

This indicates that it would take over 20,000 years for water to travel 1,100 meters from the top of the saturated zone to the lower carbonate aquifer, if the material in between were completely composed of the bedded tuff aquitard. Although these calculations are preliminary, it is evident that the vertical gradient of water potential does not provide enough driving force to create significant vertical flow beneath the bulk of Frenchman Flat.

Horizontal Flow

Estimates of the water table slope and horizontal seepage velocity beneath the Area 5 RWMS were given by Lindstrom et al. (1992) based on the Dupuit-Forcheimer approximation for a parabolic water table. Using this approximation, an uncertainty analysis was conducted, which indicated that a one-unit measurement error in the depth to the water table would require a water mound approximately ten units thick to satisfy the equation. Since no mounding of this magnitude is apparent, their conclusion was that the water table must be flat, with essentially no horizontal movement.

Corroborating evidence is available from weekly groundwater elevation measurements recorded for the three Pilot Wells. These levels can be used to estimate the water table slope directly beneath the Area 5 RWMS. Analysis of data collected over a period of a year

(UE5PW-3) is completed into the welded tuff aquifer and the bedded tuff aquitard. The completion depth and depth to water for each well is listed in Table 2.4.

Data collected from drinking water wells and the Area 5 RWMS monitoring wells indicate that the valley fill aquifer in Frenchman Flat is of sufficient yield and quality to be used as a source of drinking water (REECo, 1993d; USDOE/NV, 1993a). Background characterization data collected during calendar year 1993 are presented in Table 2.6. Mean values less than the method detection limit are noted. Data reported as ranges indicate that a single measurement was greater than the detection limit. These data indicate that the uppermost aquifer meets all the state of Nevada primary drinking water standards. Minor deviations from state of Nevada secondary drinking water standards are observed from time to time. Water Well 5C and monitoring Pilot Well UE5PW-3 are routinely more alkaline than the pH range of 6.5 to 8.5 permitted under the state of Nevada secondary standard (USDOE/NV, 1993a). Area 5 RWMS monitoring wells occasionally have been observed to exceed state of Nevada secondary standards for manganese. No chemical or radiological contaminants attributable to USDOE activities have been detected. Only naturally occurring radionuclides have been detected.

Table 2.6. Mean water quality parameters for UE5PW-1, UE5PW-2 and UE5PW-3 for 1993.

Parameter	UE5PW-1	UE5PW-2	UE5PW-3	Method Detection Limit	Units
pH	8.12	8.26	8.5		
Specific Conductance	0.392	0.384	0.375		mmhos cm^{-1}
Total Organic Carbon	n.d.†	n.d.	n.d.	1	mg l^{-1}
Total Organic Halogen	6 - 13	18 - 25	1 - 11	10	μg l^{-1}

Table 2.6. continued.					
Parameter	**UE5PW-1**	**UE5PW-2**	**UE5PW-3**	**Method Detection Limit**	**Units**
Total Cr	0 - 0.004	0 - 0.005	0 - 0.005	0.005	mg l^{-1}
Total Pb	-0.004	-0.0004	0 - 0.0003	0.0004	mg l^{-1}
Dissolved Pb	-0.004	-0.0003	0 - 0.0003	0.0004	mg l^{-1}
Total Se	0.0004 - 0.0009	0.0003 - 0.0008	0 - 0.0006	0.0004	mg l^{-1}
Dissolved Se	-0.003	0.0002 - 0.0005	0 - 0.0005	0.0004	mg l^{-1}
Total Ag	0 - 0.007	0 - 0.01	0 - 0.008	0.003	mg l^{-1}
Dissolved Ag	0 - 0.007	0 - 0.01	0 - 0.008	0.003	mg l^{-1}
Total Hg	0 - 0.0001	0 - 0.0001	0 - 0.0001	0.0001	mg l^{-1}
Dissolved Hg	0 - 0.0001	0 - 0.0001	0 - 0.0001	0.0001	mg l^{-1}
Total Fe	0.028	0.141	0.062	0.003	mg l^{-1}
Dissolved Fe	0.004 - 0.006	0.088	0.010 - 0.012	0.003	mg l^{-1}
Total Mn	0.002 - 0.003	0.003 - 0.004	0.011 - 0.012	0.001	mg l^{-1}
Dissolved Mn	0 - 0.001	0.003 - 0.004	0.011 - 0.012	0.001	mg l^{-1}
Total Na	54.8	49	51	0.05	mg l^{-1}
Dissolved Na	53	49.8	51.7	0.05	mg l^{-1}
Fluoride	2.4	1.1	1.2	0.1	mg l^{-1}
Nitrate (as NO_3)	9.7	6.0	14.1	0.04	mg l^{-1}
Chloride	9.3	9.2	8.6	0.1	mg l^{-1}
Sulfate	35	29.7	31.2	0.1	mg l^{-1}
Total Dissolved Solids	236	252	218		mg l^{-1}
Alkalinity (as $CaCO_3$)	144	139	129		mg l^{-1}
Cyanide	0 - 0.0004	0 - 3.33	0 - 0.0004	0.005	mg l^{-1}

Table 2.6. continued.					
Parameter	**UE5PW-1**	**UE5PW-2**	**UE5PW-3**	**Method Detection Limit**	**Units**
Oil and Grease	0.1 - 0.3	0.3 - 0.5	0.1 - 0.5	0.1	mg l^{-1}
Volatile Organics	n.d.	n.d.	n.d.		mg l^{-1}
Semi-Volatile Organics	n.d.	n.d.	n.d.		mg l^{-1}
Pesticides	n.d.	n.d.	n.d.		mg l^{-1}
Herbicides	n.d.	n.d.	n.d.		mg l^{-1}
Total Gross Alpha	5.1	4.2	5.1	0.7	pCi l^{-1}
Dissolved Gross Alpha	5.7	3.6	5.6	0.7	pCi l^{-1}
Total Gross Beta	4.5	4.9	4.6	0.6	pCi l^{-1}
Dissolved Gross Beta	5	5.4	4.4	0.6	pCi l^{-1}
^{3}H	-0.6	10	-0.4	9	pCi l^{-1}
^{90}Sr	0.09	0.2	0.03	0.09	pCi l^{-1}
^{99}Tc	0.7	0.5	-0.9	0.7	pCi l^{-1}
^{226}Ra	0.7	0.8	1.5	2	pCi l^{-1}
^{228}Ra	0.04	0.1	0.5	3	pCi l^{-1}
Total Uranium	0.8	1.8	9.7	5	μg l^{-1}
^{238}Pu	0	0.004	0.001	0.009	pCi l^{-1}
$^{239,240}Pu$	0.003	0.003	0.002	0.009	pCi l^{-1}
Photon Emitting	n.d.	n.d.	n.d.		pCi l^{-1}

† - n.d; not detected

The water chemistry of the wells completed in the valley fill aquifer is similar. The well completed in the welded tuff aquifer and bedded tuff aquitard, UE5PW-3, has some minor differences. Water collected from UE5PW-3 tends to have a slightly lower ionic strength and a higher pH value. Notably, the concentration of uranium is significantly higher in samples from UE5PW-3 than in samples from the other wells. This is believed attributable to the salic igneous source rock (welded tuff), which is reported to contain elevated levels of primordial radionuclides (NCRP, 1975). All measured uranium concentrations meet the proposed USEPA drinking water maximum contaminant level for uranium of 20 $\mu g\ l^{-1}$ (USEPA, 1991).

2.5 DEMOGRAPHY

Population densities in Nevada are among the lowest found in the contiguous 48 states. In 1990, the average population density of Nevada was 4.2 persons per km^2, much smaller than the average of 28 per km^2 for the contiguous 48 states (USDOC, 1990). Permanent settlement and development in the arid Mohave and Great Basin Deserts of Nevada has been restricted to areas where surface water, springs, seeps, or shallow groundwater are available or to areas near economically significant mineral resources. Since surface or shallow water resources are rare, the population of Nevada tends to be clustered around a few sites with available water. The intervening land remains largely unpopulated. Recent census data indicate that Nevada's population is overwhelmingly urban and is concentrated in Reno and Las Vegas. A map of Nevada counties, including their 1990 populations, appears in Figure 2.29. At the time of the 1990 census, urban areas with populations greater than 2,500 held 88.3 percent of the population (USDOC, 1990) and occupied only 0.9 percent of the land area (Morgan et al., 1993). Most of the remaining population resides in small rural communities with populations less than 2,500. Only 0.3 percent of Nevadans are identified as rural farm residents (USDOC, 1990).

Rural lands in Nevada outside the metropolitan areas are undeveloped, uninhabited rangeland, and mountains. The population density of areas classified as rural is only 0.5 per km^2 (USDOC, 1990; Morgan et al., 1993). This is due to both the lack of water resources and the fact that as of 1990, 82.7 percent of Nevada was owned by the U.S. Government (Morgan et al., 1993). U.S. Government-owned land can be leased to private interests for grazing and mining, but generally is uninhabited except for small transient populations of cowboys, sheep herders, hunters, campers and prospectors (USEPA, 1984). The rural counties surrounding the NTS have extremely low population densities. Nye County has a population density of 0.4 km^{-2} and Lincoln County's populationdensity is only 0.1 km^{-2}

The Las Vegas metropolitan area is the largest urban center near the NTS, with a 1990 population of approximately 741,000, or 61 percent of the then-residents of Nevada (USDOC, 1990). Las Vegas is one of the fastest growing urban areas in the United States and its population has increased significantly since the 1990 census. In recent years, residential and commercial development has increased significantly in other communities in

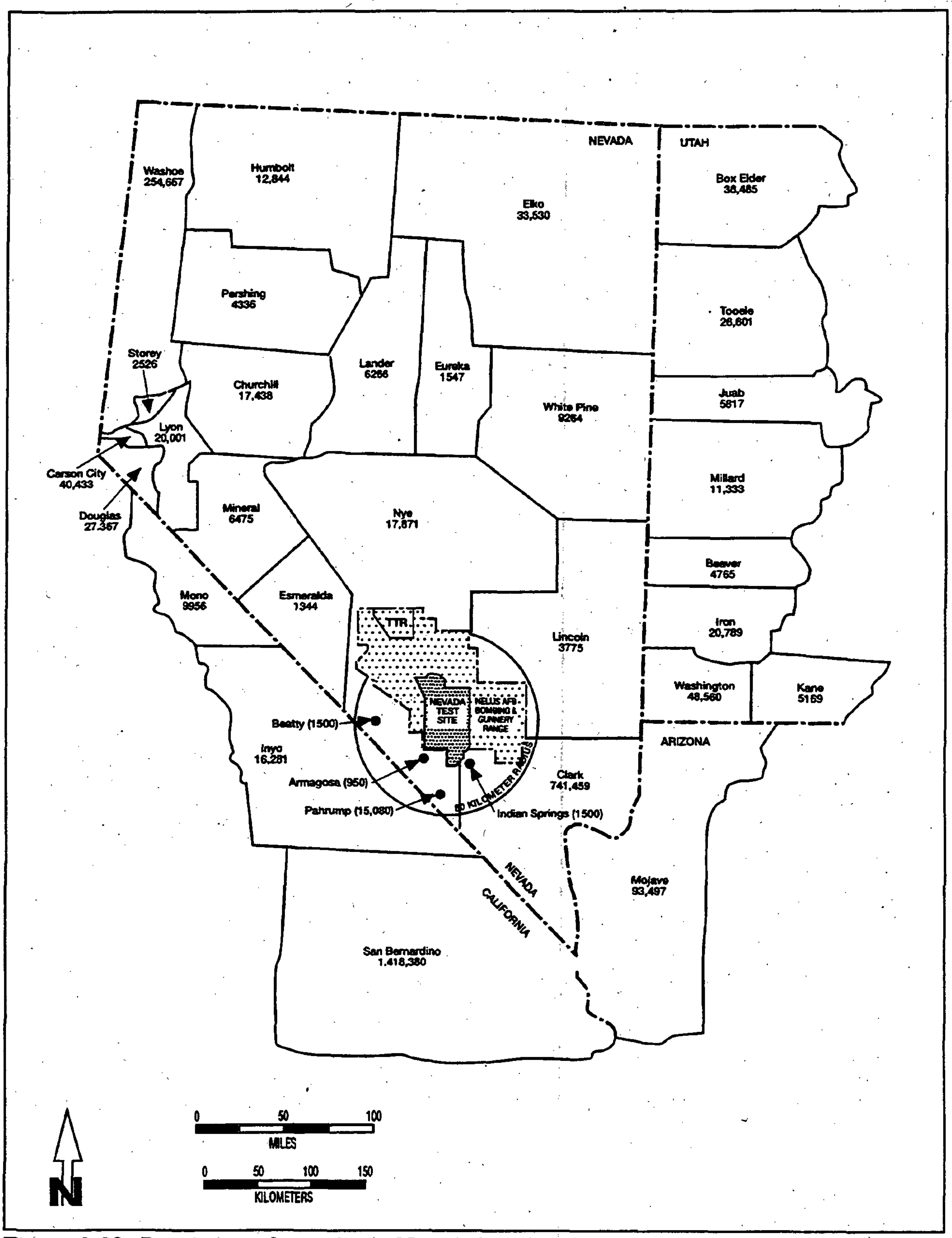


Figure 2.29 -Population of counties in Nevada based on 1990 census estimates (adapted from DOE/NV, 1993a).

southern Nevada, including Pahrump and Mesquite. Most of the population within an 80 km radius of the RWMS resides within three small rural communities: Indian Springs, Beatty and the Amargosa/Pahrump Valleys (Figures 2.1 and 2.29). The closest residents to the Area 5 RWMS reside in Indian Springs, population 1,500.

Approximately 950 persons reside in the Amargosa Valley at the Lathrop Wells farming community 50 km southwest of the RWMS (USDOE, 1993a). The Pahrump Valley, 80 km to the southwest, has a growing rural population of approximately 15,000 (USDOE, 1993a). The next largest population center in the region is Beatty (pop. 1,500), located 82 km to the west (USDOE, 1993a). There are approximately 18 small settlements, ranches and mining operations, all with populations less than 100, within the 80 km radius (USEPA, 1984). The Death Valley Monument in California, located to the west of the NTS, can have a transient population ranging from 200 to 12,000 persons (USEPA, 1984).

2.6 LAND USE

Native Americans were the first to use the lands now within the NTS. The Shoshone lived at local springs and playas over the northern NTS. Springs on the southern NTS have been used by the Southern Paiute tribe. Both groups gathered native plants, including *Oryzopsis hymenoides* (indian rice grass), *Salvia columbaria*, *Elymus cinereus* (wild rye), and pinyon nuts and hunted wild game including rabbits and *Odocoileus hemionus* (mule deer) (Reno and Pippin, 1985). Early settlers established several cattle ranching and wild horse capture operations at local springs, including Cane Springs on the western margin of Frenchman Flat (Reno and Pippin, 1985). Small mining operations have existed on the NTS in the Oak Spring District and the Mine Mountain District (Reno and Pippin, 1985). In 1928, Cane Springs supported 1,500 persons in the mining community of Wahmonie (Allred et al., 1963). Since 1940, the NTS has been a U.S. Government-owned, restricted access area, used for defense-related activities.

Today, ranching and mining remain as important land use activities in southern Nevada. Recreational activities and irrigation-based agriculture have, in recent years, become important land uses. Favorable economic conditions in Las Vegas have spurred rapid residential development in Clark County.

Geological Resources

Economically significant mining districts have been identified and exploited throughout southern Nevada. Small mining operations have existed on the NTS in the past. However, at this time no economically significant mineral resources are known to exist on the NTS (Richard-Haggard, 1983; Gustafson et al., 1993). Most mineral exploration of the NTS was conducted prior to 1940 by unsophisticated operators and little reliable data is available (Richard-Haggard, 1983). The only well known mineral deposits on the NTS are tungsten deposits in the Oak Spring District, approximately 50 km north of Area 5, which have an estimated value of $42,840 (Richard-Haggard, 1983). The known mineral deposits closest to the Area 5 RWMS are located in the Mine Mountain District, 23 km northwest of the RWMS, and the Wahmonie District, 21 km southwest of the RWMS (Gustafson et al., 1993). These areas were worked by small mining operators around the turn of the century; accordingly, their current economic potential is uncertain (Richard-Haggard, 1983). There is no information concerning the occurrence of precious metals in the valley fill alluvial sediments of Frenchman Flat or in the underlying tuffaceous or carbonate rocks (Gustafson et al., 1993). Alluvial sediments, such as those that occur throughout the Great Basin, are a potential source of zeolites (Gustafson et al., 1993). The quantity and quality of zeolites in the vicinity of the RWMS is unknown. There is no evidence that zeolites in Frenchman Flat have any greater resource value than those found throughout the Great Basin. Based on the possibility that development will occur on the NTS in the future, there is a faint possibility that sand and gravel quarrying might someday occur in Frenchman Flat.

Agriculture

The agricultural productivity of southern Nevada is limited by the arid climate, poorly developed soils, and mountainous topography. The Great Basin Desert covers central Nevada and extends over the northern two-thirds of the NTS. Northern portions of the Mohave Desert extend into southern Nevada and cover the southern third of the NTS. The Great Basin Desert is slightly cooler and wetter than the Mohave Desert and, therefore, has greater potential for agricultural use. Although Frenchman Flat lies in an area that is transitional between the two ecosystems, most floral communities surrounding the RWMS are usually considered Mohave Desert communities.

The 1987 agricultural census describes commercial agricultural land use in Nevada. These data can be used to assess the likelihood of different commercial agricultural land uses of the NTS under current economic and climatic conditions. The Great Basin Desert occupies a greater fraction of the total land area of Nevada than of the NTS. Therefore, data for the state of Nevada may not be a reliable indicator of potential agricultural land use in the dryer, hotter counties of southern Nevada. Data for Clark, Lincoln, and Nye Counties provide a more accurate indication of the potential agricultural land uses in ecosystems similar to those that occur at the Area 5 RWMS and over the NTS in general. The summary statistics reported here for southern Nevada are the means for Clark, Lincoln, and Nye Counties weighted by land area.

Total land area devoted to agriculture in Nevada is low. Overall, only 14.2 percent of Nevada's land area is within farms. In the dryer southern counties, only 2.1 percent of the land area is used for agriculture (Table 2.7). Southern Nevada farm land is most likely to be used as pasture, 89.1 percent, followed by cropland, 11.7 percent (Table 2.7). Orchard and woodlands are commercially insignificant.

Cropland is predominately used for the production of livestock feed crops (Table 2.8). Approximately 45.8 percent of southern Nevada cropland is harvested while 30 percent is used directly as pasture (USDOC, 1987). Of the harvested cropland, hay is the predominate

Richard-Haggard (1983) has reviewed the potential agricultural uses of the NTS and reported that Frenchman Flat contains 4,900 ha of irrigable soils. All irrigable soils in Frenchman Flat have poor water retention characteristics (Richard-Haggard, 1983). Nevertheless, the presence of irrigable soils, adequate groundwater supplies, and 130 to 200 frost free days per year makes it technically feasible to produce hay crops, such as alfalfa, in the basin (Richard-Haggard, 1983).

Irrigated land is a small fraction, 10.5 percent, of total farm land in southern Nevada (Table 2.9). This reflects the large amount of farm land that is uncultivated open rangeland. However, virtually all harvested crops in southern Nevada are irrigated. Harvested cropland accounts for 48.1 percent of all irrigated land, the rest being used as pasture. Again, most harvested crops are hay crops, intended for consumption by livestock. Richard-Haggard (1983), noting that only 5 percent of irrigable land in Nevada is in use, concluded that current demand for irrigable land is low. The cost of obtaining deep groundwater resources may in part explain this observation. Irrigation of farm land in southern Nevada most commonly occurs where surface water or shallow groundwater is available. These conditions do not occur in Frenchman Flat near the Area 5 RWMS.

Pastureland in southern Nevada is 95.9 percent uncultivated, unirrigated rangeland. Beef cattle are numerically the most common livestock produced, followed by sheep (Table 2.10). Hogs and chickens are raised in small numbers (USDOC, 1987). With the exception of Clark County, commercial milk production in southern Nevada is insignificant. Several Grade A dairy herds occur in Clark County, but all are greater than 100 km from the NTS (USEPA, 1984). In 1984, the USEPA reported 83 family dairy cows and 397 family milk goats in Nye, Lincoln, and Clark Counties (USEPA, 1984).

Table 2.7. Total land area and farm land in southern Nevada for 1987 (from USDOC, 1987).

Land Use	Nevada	County		
		Clark	Lincoln	Nye
Land Area (ha)	28,439,700	2,048,900	2,754,400	4,700,100
Farm Land Area (ha)	4,042,254	27,427	18,771	149,903
% Land Area in Farms	14.2	1.3	0.7	3.2
% Farm Land Used as Cropland	8.0	16.8	37.6	7.6†

Table 2.7. continued.				
Land Use	**Nevada**	**County**		
		Clark	**Lincoln**	**Nye**
% Farm Land Used as Pasture	89.2	74.3	72.9	93.8
% Farm Land Used as Orchard	0.005	0.2	0.5	0.02
% Farm Land Used as Woodland	0.09	0.5	‡	‡

† - Value Based on 1982 data

‡ - Single operator reporting

Table 2.8. Cropland in Nevada and southern Nevada by use and crop grown for 1987 (from USDOC, 1987).

Cropland	**Nevada**	**County**		
		Clark	**Lincoln**	**Nye†**
% Harvested	65.5	53.7	41.1	45.6
% of Cropland that is Harvested and Irrigated	65.3	53.7	41.1	45.6
% Cropland Used as Pasture	26.0	30.1	34.1†	‡
% Other Cropland (Idle)	8.5	16.2	16.0†	‡
% Cover Crops not Harvested or Grazed	0.7	1.3		‡

† - Value based on 1982 data

‡ - Single operator reporting

Table 2.9. Irrigated land and irrigated land by use in Nevada and southern Nevada for 1987 (from USDOC, 1987).

Irrigated Land	Nevada	County		
		Clark	Lincoln	Nye
% of Farm Land Irrigated	7.8	11.1	30.9	7.9
Irrigated Land by Use				
% Harvested Cropland	67.3†	78.3	50.0	39.5
% Pastureland	32.7	22.1	50.0	60.5

† - Value based on 1982 data

contents for more than half of all months. Forbs were observed in rumen contents in

significant numbers only during the late summer (Smith et al., 1972). *Salsola* spp. were the dominate forbs, reaching frequencies in rumen contents up to 70 percent (Smith et al., 1972). Later studies conducted during summer months found that cattle rumen contents were 93 percent grasses, predominately *Oryzopsis hymenoides, Sitanion hysterix*, and *Bromus tectorum* (USEPA, 1981). Forbs accounted for only 2.8 percent of rumen contents and shrubs 4.2 percent (USEPA, 1981). *Atriplex canescens* (four-wing salt brush) was the most commonly consumed shrub (USEPA, 1981). Mohave Desert communities offer few browse species, notably *Ambrosia dumosa,* and limited amounts of winter annual grasses and forbs (Stoddart and Smith, 1955). Richard-Haggard (1983) estimated that *Larrea* communities such as those that occur at the Area 5 RWMS could provide 0.045 animal unit months (AUM) per hectare. An animal unit month is the forage necessary for complete sustenance of one cow or 5 sheep for one month (USDOC, 1987). The grazing potential of land surrounding the RWMS can be estimated from plant biomass. The grazing studies suggest that annual grasses are the preferred food of cattle grazing on NTS. Beatley (1969) estimated a mean annual plant biomass for Frenchman Flat *Larrea* communities of 66 kg ha^{-1}. Assuming a dry weight consumption rate for cattle of 8 to 12 kg day^{-1}, the total grazing potential for Frenchman Flat *Larrea* communities can be estimated to be 0.061 to 0.091 AUM per hectare. Productivity of additional NTS plant communities are provided in Table 2.11. In 1985, the Bureau of Land Management issued grazing permits for 17,542,240 ha of land in Nevada with an estimated total AUM of 2,563,758 giving an average for Nevada of 0.15 AUM ha^{-1} (USDOI, 1985).

Table 2.11. AUM ha^{-1} for various floral communities on the NTS (from Richard-Haggard, 1983).

Floral Community	AUM ha^{-1}
Larrea	0.045
Artemisia	0.024
Coleogyne	0.0086
Larrea - Coleogyne	0.024
Grayia - Lycium	0.033
Atriplex	0.02
Lycium pallidum	0.033
Pinyon - Juniper	0.014

2.7 ECOLOGY

2.7.1 Flora

Plants affect LLW disposal site performance by transporting contamination to the land surface, by introducing contamination into trophic pathways, and by transpiration of infiltrating water. The productivity of floral communities in southern Nevada is limited by the harsh climate and poor soils. Most areas support sparsely-vegetated communities of perennial shrubs. Many measures of the productivity of these communities, including net above ground primary productivity and standing biomass, are highly variable with time and location. The quantity and timing of precipitation is critical in determining survival, growth, and reproduction of many species. Although productivity can be low, floral diversity is high. O'Farrell and Emery (1976) report 711 taxa of vascular plants for the NTS and its environs. As many as 70 species per 1,000 m^2 have been reported (Beatley, 1976).

Historically, the flora of the NTS have been grouped into three major or regional communities: the Mohave Desert community occurring over southern Nevada, the Great Basin Desert community occurring over central Nevada, and a transitional community interspersed between the two (Beatley, 1976; O'Farrell and Emery, 1976). Within each regional community, local communities can be identified via recurring assemblages of numerically dominant and co-dominant perennial shrubs or trees (Beatley, 1976; O'Farrell and Emery, 1976). Local communities grade gradually into one another as edaphic and climatic conditions change, forming a complex patchwork of plant communities. Community composition can be quite complex, with no two locations having the same species composition (Beatley, 1976).

Communities of the Mohave Desert occur over the southern third of the NTS, on the bajadas and mountain ranges at elevations below 1,200 m. They are limited to areas with mean minimum temperatures greater than $-2\,°C$ and average annual rainfall less than 18.3 cm (O'Farrell and Emery, 1976). Mohave Desert communities can have highly variable floristic compositions, but all share a shrub clump form dominated by *Larrea tridentata* (creosote bush) and variable co-dominant shrubs (Beatley, 1976). Shrub coverage varies from 7 to 23 percent for Mohave Desert communities found on the NTS (Beatley, 1976). Herbaceous species including perennials and winter annuals can be uniformly interspersed between shrub clumps or only associated with shrub clumps, depending on soil and climatic conditions (Beatley, 1969; Beatley, 1976). Growth of herbaceous perennials and reproduction and growth of winter annuals is regulated by autumn rains and can vary significantly from year to year with rainfall (Beatley, 1976; Bowers, 1987). Winter annuals in particular undergo mass germinations after heavy autumn rains and reach levels of cover as high as 30 percent (Beatley, 1976). Summer annuals (ephemerals) may appear briefly after late summer rains and reach area coverages up to 8 percent (Beatley, 1976).

Beatley (1976) identified three Mohave Desert bajada communities based on the numerically co-dominate shrub species present. The communities were: the *Larrea tridentata - Ambrosia dumosa* (bur sage) community found on loose deep soils, the *Larrea - Lycium andersonii* (desert thorn) - *Grayia spinosa* (hop sage) community found at elevations between 1,000 to 1,200 m, and the *Larrea - Atriplex confertifolia* (shadscale) community found on calcareous soils with well developed pavements and caliche layers (Beatley, 1976). Numerous herbaceous species occur within these communities. See Beatley (1976) for complete descriptions.

Assemblages grouped among transitional desert communities occur under two different situations. Some assemblages occur along elevation gradients between Mohave Desert and Great Basin Desert communities. Others occupy the bottoms of closed basins where cold air accumulates during the night (Beatley, 1976). These communities, although considered transitional, may be completely surrounded by Mohave or Great Basin Desert communities. On the NTS, two transitional communities, *Coleogyne* and *Larrea - Grayia - Lycium*, occur along elevation gradients between Great Basin and Mohave Desert communities. *Coleogyne ramossima* (blackbush) grows in nearly pure stands on upper elevation bajadas that are beyond the moisture range of Mohave Desert communities (Beatley, 1976). *Larrea - Grayia - Lycium* assemblages occur on higher bajadas, often below *Coleogyne* communities (Beatley, 1976). Three transitional communities, *Grayia - Lycium, Lycium pallidum - Grayia*, and *Lycium shockleyi - Atriplex* are associated with the lower elevations of closed basins (Beatley, 1974; Beatley, 1976). Romney et al. (1973) report that, in addition to cold night time temperatures, soil texture, and salinity are also important in controlling the distributions of these communities. Shrub coverage in transitional communities averages 29 percent (O'Farrell and Emery, 1976).

Great Basin Desert communities occur within basins and on mountains at elevations above 1,500 m (O'Farrell and Emery, 1976). These locations are less arid due to lower temperatures and greater precipitation (Beatley, 1976). In comparison to Mohave Desert communities, Great Basin Desert communities tend to have more herbaceous perennials, fewer annuals, and shrub clumps tend to be closer together or absent (Beatley, 1976). These communities are dominated by either *Atriplex spp.* (*A. confertifolia* or *A. canescens* (four-winged salt bush)) or *Artemisia spp.* (*A. tridentata* (big sagebrush) or *A. nova* (black sagebrush)) (Beatley, 1976). Above 1,800 m, *Artemisia spp.* - *Pinus monophylla* (pinyon pine) - *Juniperus osteosperma* (juniper) associations are common (Beatley, 1976).

Undisturbed communities on the NTS are considered climax assemblages (Beatley, 1976). However, steady-state conditions may rarely be observed due to slow vegetative growth and shifting climatic conditions (Hunter, 1992a). A natural succession of plant communities does not occur after disturbance, but rather plants from the surrounding climax communities become re-established directly (Beatley, 1976). Some introduced species, however, are associated with disturbed areas and can delay revegetation by native species (O'Farrell and Emery, 1976). These include the winter annual grasses *Brumus rubens* (downy chess) and *B. tectorum* (cheatgrass) and the Russian thistles, *Salsola iberica* and *S. paulsenii* (O'Farrell and Emery, 1976). Populations of these introduced species have apparently been increasing

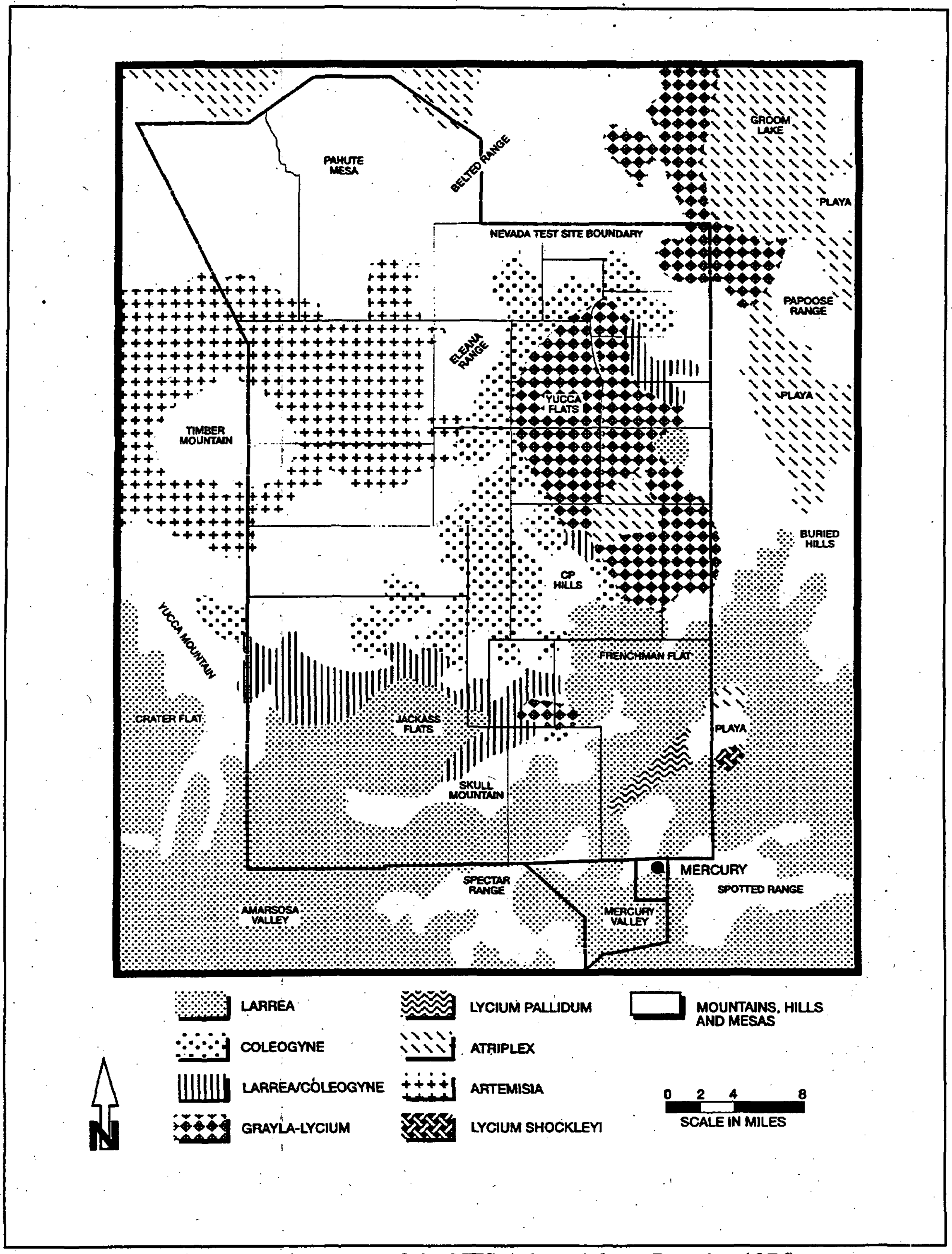


Figure 2.30 - Major vegetation types of the NTS (adapted from Beately, 1976).

A transitional desert *Lycium pallidum* - *Grayia* community covers a 2-km wide strip, extending 7 km southeast of the playa (Figure 2.30) (Beatley, 1976; EG&G, 1982). A *Lycium shockleyi* transitional desert community also occurs south of the playa. An *Atriplex confertifolia* community of the Great Basin Desert extends over a triangular area north of the playa (Beatley, 1976). The boundary between these three communities and the surrounding *Larrea* communities is quite distinct and has variously been attributed to cold night time temperatures (Beatley, 1974) and high soil salinity, poor soil aeration, and poor soil drainage (Romney et al., 1973).

Mohave Desert plant communities are characterized by low areal coverage, low standing biomass, low productivity, and high relative biomass turnover (Beatley, 1976; Strojan et al., 1979). Numerous investigators have estimated above-ground plant biomass values for *Larrea* communities, such as those that occur in the vicinity of the Area 5 RWMS (Table 2.12). Estimates of above-ground standing biomass and net annual productivity can be used to estimate the grazing capacity of the land.

Plant biomass is highly correlated with mean annual rainfall, (O'Farrell and Emery, 1976), and varies significantly from year to year and with location. Much less is known about below-ground biomass, but it has been estimated at approximately 45 percent of above-ground biomass (Wallace et al., 1974).

In absolute terms, net primary productivity is low in these communities, but may be large relative to standing biomass. Romney et al. (1977) and Romney and Wallace (1977) have estimated that production is from 1 to 10 percent of standing biomass annually. O'Farrell and Emery (1976) report that most annual production is attributable to winter annuals. Winter annual standing biomass, which represents the production of a single growing season, can vary from 0 to 616 kg ha^{-1}, but a mean value of 90 kg ha^{-1} has been recorded for the NTS (Beatley, 1969). In contrast, Romney and Wallace (1979) found that perennial shrubs produced the greatest biomass in Rock Valley over a three-year study period. Their estimates of primary productivity as the mean dry weight and one standard deviation were 159 ± 103 kg ha^{-1} yr^{-1} for annuals, 407 ± 93 kg $ha^{-1} yr^{-1}$ for perennials and 566 ± 187 kg ha^{-1} yr^{-1} total. Over two consecutive years Bamberg et al. (1976) reported above-ground net primary productivity of perennials in Rock Valley to be 135 kg ha^{-1} and 436 kg ha^{-1}.

Annual litter fall may be a significant fraction of standing biomass and net primary productivity. Estimates of herbivory are generally low in desert environments, suggesting

Table 2.12. Above-ground living dry weight biomass of NTS plant communities as reported by various investigators for Frenchman Flat *Larrea* communities.

Source	Community/ Location	Perennials ($kg\ ha^{-1}$)	Annuals ($kg\ ha^{-1}$)	Total ($kg\ ha^{-1}$)
Beatley (1969)	*Larrea* Frenchman Flat	-	0 - 442 Mean: 66	
Romney et al. (1973)	*Larrea* Frenchman Flat	113 - 923 Mean: 466	-	
Romney et al. (1977)	*Larrea - Ambrosia* GMX Site	2,200	-	
Hunter and Medica (1987)	*Larrea - Ambrosia* Frenchman Flat	2,047 - 4,259 Mean: 3,020	-	
Hunter (1992a)	*Larrea - Ambrosia* Frenchman Flat	3,491 - 3,527 Mean: 3,509	-	
Hunter (1992b)	*Larrea - Ambrosia* Frenchman Flat	1,640 - 3,150 Mean: 2,204	-	
Hunter (1992b)	*Larrea* GMX Site	2,060 - 2,520 Mean: 2,290	-	
EG&G (1982)	*Larrea* Frenchman Flat	1,375	57	1432

that a significant fraction of plant biomass becomes soil detritus each year (Strojan et al., 1979). Strojan et al. (1979) estimated that dry litter fall from perennial shrubs in Rock Valley over a two year interval was 217 $\pm$ 141 kg ha^{-1} yr^{-1}. Total dry litter fall, including annuals, was estimated to be 362 $\pm$ 237 kg ha^{-1} yr^{-1} (Strojan et al., 1979). Annual litter fall as a percent of standing above-ground biomass among perennial species ranged from 7 to 83 percent (Strojan et al., 1979). Annual litter fall was estimated to be from 81 to 99 percent of net above-ground productivity (Strojan et al., 1979).

Few studies have described the rooting depths of Mohave Desert plants and assessed their potential to penetrate a waste repository. Wallace and Romney (1972) have described the root systems of several plants excavated from a wash in Rock Valley on the NTS and reported a maximum depth of 168 cm. The study site was selected because of the absence of caliche hard pan layers that can restrict rooting depths. The reported maximum root depth for individual plants were 86 cm for *Ambrosia dumosa*, 81 cm for *Hymenoclea salsola*, 91 cm for *Ephedra nevadensis* (Mormon tea), 168 cm for *Larrea tridentata*, 64 cm for *Ceratoides lanata* (winter fat), 122 cm for *Lycium andersonii* (desert thorn), and 97 cm for *Grayia spinosa* (Wallace and Romney, 1972). Root systems generally took the form of a

The complex assemblage of Mohave and Great Basin Desert plant communities on the NTS supports a diverse fauna. Large variations in animal population densities are observed. These variations are correlated with the quantity and timing of rainfall and its effects on primary productivity. Casual daytime observers rarely encounter desert fauna, especially the larger mobile species. Many animals avoid high temperatures and predation by burrowing

Invertebrates, particularly insects, are the most abundant and diverse element of the NTS environments are a consequence of USDOE operations. It is assumed that they will not exist after USDOE operations cease.

Forty-six mammalian species have been reported for the NTS (O'Farrell and Emery, 1976). Although many of the larger species are game species, they are rare or transitory visitors to the Area 5 RWMS. Fossorial species, particularly rodents, are common. Rodents account for half of all known NTS mammalian species and are numerically the most common (Allred et al., 1963). Rodent population densities and reproduction are highly correlated with production of winter annuals. Mohave Desert *Larrea-Ambrosia* communities can support high rodent population densities, but generally have low species diversity (Allred et al., 1963). *Spermophilus tereticaudus* (round-tailed ground squirrel), *Dipodomys merriami* (Merriam's kangaroo rat), *Onychomys torridus* (southern grasshopper mouse), and *Peromyscus eremicus* (cactus mouse) are found commonly in Mohave Desert communities. Eleven species of rodents and a bat specie have been reported from various surveys in Frenchman Flat. They include a bat, *Pipistrellus hesperus* (western pipistrelle), and the rodents, *Thomomys umbrius* (southern pocket gopher), *D. merriami*, *D. microps* (Great Basin kangaroo rat), *D. deserti* (desert kangaroo rat), *Perognathus longimembrinus* (little pocket mouse), *P. formosus* (long-tailed pocket mouse), *Neotoma lepida* (desert wood rat), *O. torridus, Ammospermophilus leucurus* (white-tailed antelope squirrel), *Spermophilus tereticaudis* (round-tailed ground squirrel) and *Peromyscus maniculatus* (deer mouse) (Bradley and Moor, 1975; Bradley and Moor, 1978; Bradley and Moor, 1976; Bradley et al., 1977; Hunter et al., 1991).

Fossorial rodent populations densities in *Larrea - Ambrosia* communities are among the highest found on the NTS (O'Farrell and Emery, 1976). Estimates of rodent population densities at two sites in northern Frenchman Flat are reported in Table 2.13. These data are based on numbers of animals collected by traps. Since trapping success can depend on the behavior of the species and its level of activity at the time of collection, trapping data may provide a biased estimate of population densities. Nevertheless, kangaroo rats (*Dipodomys*) and the little pocket mouse (*Perognathus longimembrinus*) appear to account for greater than 90 percent of the population (Hunter and Medica, 1987; Hunter, 1992a). Population densities apparently vary widely over time. Ground squirrels are reported to be uncommon (Hunter et al., 1991). Unfortunately, pocket gophers are not sampled by trapping techniques used in past studies and estimates of their population densities are not available (Hunter et al., 1991).

Table 2.13. Population density of rodents and rabbits in *Larrea* communities near the Area 5 RWMS.

Species	Population Density (ha^{-1})		
	Bradley and Moor,	Hunter and	Hunter, 1992a

Quantitative predictions of the effects of burrowing fauna on site performance are difficult to make due to the lack of relevant data. The quantity of soil transported to the surface is dependent on population density, soil characteristics, and seasonal activity levels. The transport processes itself is complex. Some species, such as pocket gophers, are reported to selectively transport cobbles and gravels to the surface (Hansen and Morris, 1968; Hankonson et al., 1982). Burrows are frequently reworked and refilled, presumably with both clean and contaminated material, producing a complex mixing of surface soils (Thorne and Andersen, 1990). Burrowing activity is apparently variable in time and with location (Voslamber and Veen, 1985; Thorne and Andersen, 1990).

Burrowing animals may directly affect site performance by burrowing into waste cells and transporting contamination to the surface. Direct intrusion into waste by mammals appears unlikely, as most mammals only burrow to shallow depths. Anderson and Allred (1964) examined 30 kangaroo rat (*Dipodomys microps*) burrows on the NTS. They reported a maximum burrow depth of 61 cm and a mean depth of 33 cm. Burrowing behavior was affected by the texture of the soil (Anderson and Allred, 1964). Winsor and Whicker (1980) found that the pocket gopher (*Thomomys talpoides*) rarely burrows below 30 cm, and its average burrow depth on their Colorado study site was 13.4 cm. Hankonsen et al. (1982) recorded the depths of pocket gopher (*T. bottae)* burrows at a LLW site in northern New Mexico. None of the burrows penetrated below 100 cm.

Significant numbers of burrowing animals occur within Frenchman Flat and their activities may influence site performance. Direct intrusion into buried waste by vertebrates appears unlikely. Shallow vertebrate burrowing activity may affect site performance by mixing surface soils and by altering cap hydraulic properties and stability. Invertebrate burrowing, although much less studied at the NTS, appears to have the potential for direct intrusion into the waste.

2.8 RADIOLOGICAL ENVIRONMENT

Persons residing in unrestricted areas adjacent to the NTS and future residents occupying the site will be exposed to internal and external sources of ionizing radiation from natural and man-made sources. Understanding these sources and their significance is important for interpreting performance assessment results and for interpreting site performance based on environmental monitoring results. The National Council on Radiation Protection (NCRP) has reported the average dose equivalent received by United States residents from background and man-made sources to be approximately 360 mrem yr^{-1} (NCRP, 1987b). Average United States residents are estimated to receive approximately 82 percent of their annual effective dose equivalent from natural sources (NCRP, 1987b). This corresponds to an effective dose equivalent of approximately 300 mrem yr^{-1}, most of which is attributable to inhalation of ^{222}Rn progeny (NCRP, 1987b). Natural sources of radiation exposure include external irradiation from cosmic particles and primordial radionuclides. Exposure to cosmogenic and primordial radionuclides present in air, water, and food are a natural source of internal radiation doses. Man-made sources of radiation are, on average, less important sources of exposure and include, in descending order of importance, medical procedures, consumer products, and industrial sources (NCRP, 1987b). Industrial sources, which include USDOE operations among many other sources, and nuclear weapons testing, are estimated to account for approximately 0.8 percent of the average annual effective dose equivalent for United States residents, or approximately 2 mrem (NCRP, 1987b).

The NCRP data presented above is for average United States residents. Current and future residents of the NTS and its environs may be potentially exposed to radionuclides at levels greater than average. Potential sources of exposure in Frenchman Flat, in addition to waste disposal operations, include above and belowground nuclear weapons tests and safety tests. Between 1951 and 1962, 14 nuclear devices were detonated in the atmosphere over the Frenchman Flat playa. In 1965, three underground nuclear tests were conducted northwest of the playa, approximately 3.5 km south of the RWMS (Figure 2.3). Two more underground tests were conducted in 1966 and 1968, approximately 2.4 km northeast of the RWMS. During 1954 and 1955, several safety tests were conducted at the GMX site, 1.8 km southeast of the site. Safety tests involve the destruction of nuclear weapons components and result in the release of radioactive material, most commonly plutonium. In addition, several hundred announced above and belowground nuclear weapons tests have been conducted in Yucca Flat. Yucca Flat is a north-south trending closed basin, beginning 13 km northwest of the RWMS and extending approximately 37 km north. Numerous safety tests have been conducted in Plutonium Valley, a north-south trending valley draining into Yucca Flat. Plutonium Valley lies 11 km north of the RWMS and is separated from Frenchman Flat by French Peak and the Halfpint Range.

Radiological surveys of the surface soils of Frenchman Flat have shown that small localized areas of contamination associated with ground zeros are present on the Frenchman Flat playa and at the GMX site. Most soils of the basin contain concentrations of fallout radionuclides that are consistent with levels expected from global fallout. Barnes et al., (1980) surveyed the surface soils of the playa and identified three ground zero areas that were above background: Hamilton, Bfa and Small Boy. These areas cover approximately 5.7 km^2 of the Frenchman Flat playa (McArthur, 1991). The radionuclides identified and their maximum contour concentrations, as of 1980, were ^{60}Co (25 pCi g^{-1}), ^{137}Cs (25 pCi g^{-1}), ^{152}Eu (150 pCi

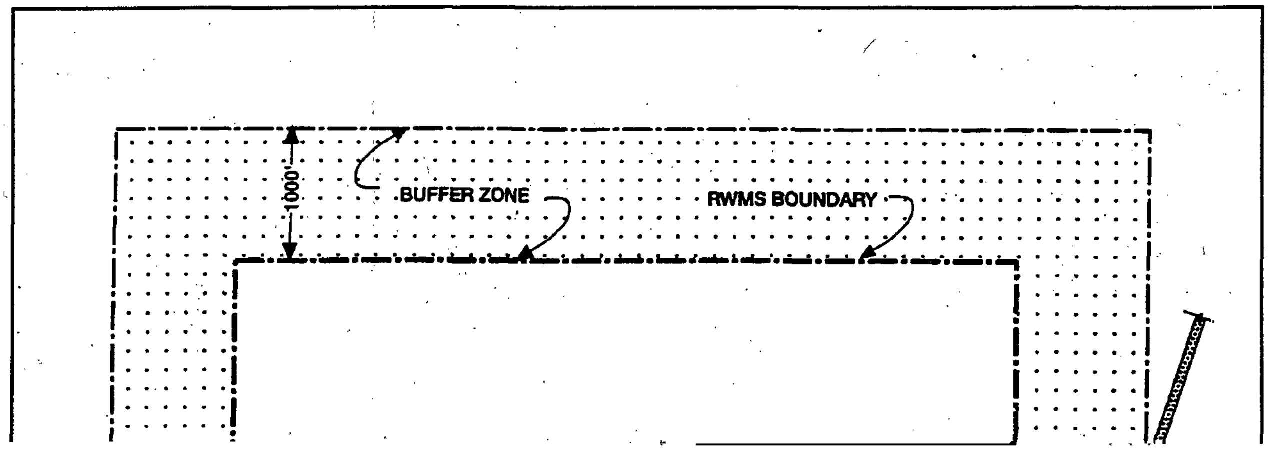
g^{-1}), ^{155}Eu (25 pCi g^{-1}), ^{239}Pu (400 pCi g^{-1}), and ^{241}Am (150 pCi g^{-1}) (Barnes et al., 1980). The other area of surface contamination in Frenchman Flat is the GMX site. Gilbert et al. (1975) reported ^{239,240}Pu concentrations for soil and vegetation from five regions or strata encompassing 0.12 km^2 at the GMX ground zero. The mean ^{239,240}Pu concentrations for soil and vegetation for the highest concentration strata sampled were, respectively, 7.3 nCi g^{-1} and 0.31 nCi g^{-1} (Gilbert et al., 1975). McArthur (1991) measured the soil concentration of radionuclides, using in situ gamma spectrometry and soil sampling and analysis, at four sites in Area 5 and estimated the total inventory. The sites, Frenchman Flat playa, GMX, and two underground testing complexes, were chosen based on the results of previous aerial surveys (McArthur, 1991). The Area 5 RWMS and its surrounding soils were not sampled.

Table 2.14. Estimated surface soil radionuclide inventory for Area 5 as of January 1, 1990, excluding the Area 5 RWMS (from McArthur, 1991).

Radionuclide	Radionuclide Inventory (Ci)	
	Frenchman Flat Playa	GMX
^{60}Co	1.0	
^{90}Sr	1.1	
^{137}Cs	0.4	
^{152}Eu	12.1	0.2
^{154}Eu	0.8	
^{238}Pu	0.1	
$^{239,240}Pu$	3.4	1.4
^{241}Am	0.4	0.2

Table 2.6 illustrates groundwater monitoring results for the uppermost aquifer, which indicate that radioactive contamination is not present at the three Pilot Well locations (REECo, 1993b). Tritium concentrations have been found to be less than the minimum detectable activity of 15 pCi l^{-1} (REECo, 1993b). Tritium is among the most mobile radioactive contaminants produced by nuclear weapons. Its absence in the uppermost aquifer suggests that contamination from nuclear weapons tests has not migrated to the aquifer beneath the Area 5 RWMS. Only naturally occurring primordial radionuclides, including uranium and progeny of ^{222}Rn, have been detected in the uppermost aquifer (REECo, 1993b). The activities of uranium, gross alpha, gross beta, and the activity of ^{222}Rn estimated from progeny fall with the range of values reported by USEPA for groundwater derived drinking water supplies in Nevada (USEPA, 1985). It remains unknown if contaminates are migrating from underground nuclear test cavities in the vicinity of the RWMS. If any such plumes exist, they will confound interpretation of future environmental monitoring results and may contribute to doses received by the public.

Routine radiological monitoring at the NTS includes onsite monitoring conducted by the USDOE and its contractors and offsite monitoring conducted by the USEPA. The onsite monitoring program includes collection of air, soil, vegetation, and biota samples at the Area 5 RWMS and at the residence closest to the RWMS, which is located in Indian Springs, Nevada. Ambient photon exposure rates are monitored by thermoluminescent dosimetry onsite and by pressurized ion chamber offsite. The only man-made radionuclide detected at the Area 5 RWMS in 1992 was tritium in air (USDOE/NV, 1993a). Reference man would receive a CEDE of 0.07 mrem if exposed to the highest tritium concentration detected, 2.7×10^{-10} μCi ml^{-1}, for an entire working year. In 1992, residents of Indian Springs were estimated to receive a CEDE of 0.007 mrem from all NTS airborne effluents and 0.04 mrem


1000'
BUFFER ZONE
RWMS BOUNDARY

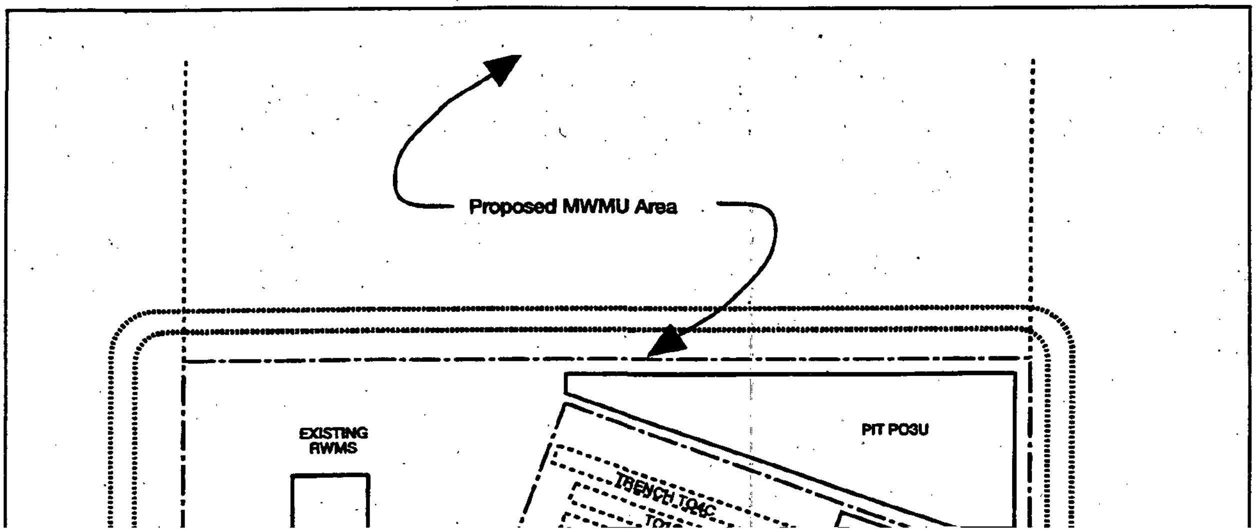

Proposed MWMU Area
EXISTING RWMS
PIT PO3U
TRENCH T04C

Table 2.15. Existing support structures at the Area 5 RWMS and their functions.

Building No.	Functional Description
5-6	The Special Projects Lab includes the soils test lab, an equipment calibration room, and a core sample storage area.
5-7	Administrative offices.
5-10	Health physics support offices.
5-21	Houses equipment and stores bottled gas and flammable materials (no utilities).
5-19	Part of water system that pumps water to 5-6 and 5-7. System also provides a potable water source for Area 5.
5-18	Used as a craft assembly point and lunch area.
183400	Waiting area for truck drivers (no water or sewer).
178667	Contains sampling pumps and reservoirs for tritium migration tracking by University of California (no water or sewer).
186084	Used to support HWAS operations (no water or sewer).
202,616.00	Contains equipment including an electronic microscope, lab balances, and a sieve shaker (no water or sewer).
202617	Contains scientific equipment (no water or sewer).
183261	Used for storing radiological logistic supplies (no water or sewer).
712240	Provides office space for the HPD supervisor (no water or sewer).
	Provides showers and lockers for use by Area 5 RWMS

burial. Eight trenches (T01U, T02U, T04U, T06U, T01C, T03C, T05C, T06C) were filled and closed during this period. Starting in 1978, NTS began accepting LLW generated by offsite USDOE facilities. From 1978 until the implementation of USDOE Order 5820.2A, in 1988, three pits and trenches (P01U, P02U, T07U) were filled and closed. Ten GCD boreholes were operationally active during this interval (1978 - 1988). Since the implementation of Order 5820.2A on September 26, 1988, six pits and trenches (P03U, P04U, T03U, P06U, T02C and T04C) and two GCD boreholes have been active. The performance assessment addresses these units only.

Currently, the Area 5 RWMS is open and receiving LLW from the NTS and offsite generators. Mixed waste disposal operations have ceased since 1990. The Area 5 RWMS does not accept non-radioactive hazardous waste or non-radioactive solid waste. All hazardous waste generated onsite is transferred to an offsite commercial treatment, storage, and disposal facility. Non-radioactive solid wastes are disposed of at solid waste landfills not associated with the Area 5 RWMS.

2.9.1 Shallow Land Burial

LLW is currently landfilled in the Area 5 RWMS in shallow unlined land disposal trenches and pits. Only two unclassified and two classified pits and trenches have received waste since the implementation of Order 5820.2A. These are Pit 4 (P04U), Pit 3 (P03U), and Classified Trenches 2 and 4 (T02C and T04C) (Figure 2.32). All the pits and trenches active since 1988 remain open and are available to receive waste with the exception of the MW cell (PO3U) (Table 2.16). Two cells, Trench 3 (T03U) and Pit 6 (P06U), are open but have not received any waste for permanent disposal. Trench 3 is currently used for storage of special case thorium waste. This waste will be buried at greater depth, to allow attenuation of ^{222}Rn fluxes. Current plans are to place the thorium waste beneath the existing floor of Pit 6 (P06U). Pits and trenches active since 1988 and their approximate volumes are listed in Table 2.17. Pit 4 (PO4U) has received the largest volume of waste since 1988. This pit has received exclusively LLW. Pit 3 (PO3U) has received low volumes of LLW and MW and has been inactive since MW disposal was suspended in 1990. Classified trenches TO2C and TO4C hold relatively small volumes of LLW and are nearly full at this time. The total area covered by the pits and trenches in the LLWMU is 5.1×10^4 m^2 or 5.1 ha out of the 37.2 ha in the LLWMU. All other pits and trenches indicated in the Area 5 RWMS (Figure 2.32) were filled prior to 1988 and are awaiting final closure.

Table 2.16. Date of use and current status of pits and trenches receiving wastes since the inception of USDOE Order 5820.2A.

Cell Name	Opened	Status
Pit 4 (PO4U)	1988	Open, ~80% full
Trench 3 (TO3U)	1984	Open, Empty

2.9.1.1 Mixed Waste Disposal

Pit 3 is the only disposal unit in the Area 5 RWMS that has received mixed waste. Disposal of low-level (non-hazardous) waste began in Pit 3 in January of 1987. Mixed wastes were disposed of in Pit 3 for the first time in September of 1987, when the state of Nevada [redacted] monument records the cell number, the survey coordinates, and the date the cell was opened and closed. The temporary closure cap will remain until final closure.

2.9.2 Greater Confinement Disposal

In 1980, the USDOE's National LLW Management Program began reviewing alternatives to shallow land burial of LLW. Although the majority of LLW is routinely and safely disposed of using shallow land burial, a portion of the waste was considered unsuitable for shallow land burial because of its high specific activity or potential for migration into biopathways. In 1981, USDOE's Nevada Operations Office began a project to demonstrate the feasibility of greater depth burial in the alluvial sediments of the NTS. The purpose of the project, termed Greater Confinement Disposal (GCD), was to investigate the disposal of LLW at a depth sufficient to minimize or to eliminate natural environmental intrusion processes (animal burrowing, rain water infiltration, plant rooting) into the waste zone. The project was also designed to substantially reduce the potential for inadvertent human intrusion.

GCD disposal units are 36 m vertical boreholes drilled in the desert alluvium. The boreholes are unlined, except for the upper 3 m which is cased with a corrugated steel culvert. Each is approximately 3 m in diameter with a total depth of 36 m. Waste packages are placed in the bottom of the GCD boreholes to approximately 21 m below the land surface. The holes are then backfilled with native soil. A 1.8-m long concrete monument, indicating the location and contents of the borehole, is placed approximately 1.5 m below the surface in each hole. Figure 2.33 shows the design of a GCD borehole. Waste disposed of in GCD boreholes includes TRU waste, high-specific activity tritium waste, irradiated fuel rod cladding, and sealed sources. Wastes disposed of since the inception of USDOE Order 5820.2A contain only ^3H and depleted uranium.

GCD boreholes were used for the disposal of waste from 1983 through 1989. Thirteen GCD boreholes were developed during this period within the LLWMU (Figure 2.34). The first unit was experimental and is known as GCD Test or GCDT. Seven cells have been filled and operationally closed. Three GCD boreholes have received waste and remain open. Three GCD cells are empty. Table 2.18 lists the GCD boreholes and their status. GCD boreholes have been designated with sequential numbers and a one letter code denoting the classification status.

Two GCD boreholes (7C and 10U) have received waste since the implementation of USDOE Order 5820.2A. The GCD inventory used in the performance assessment has been limited to

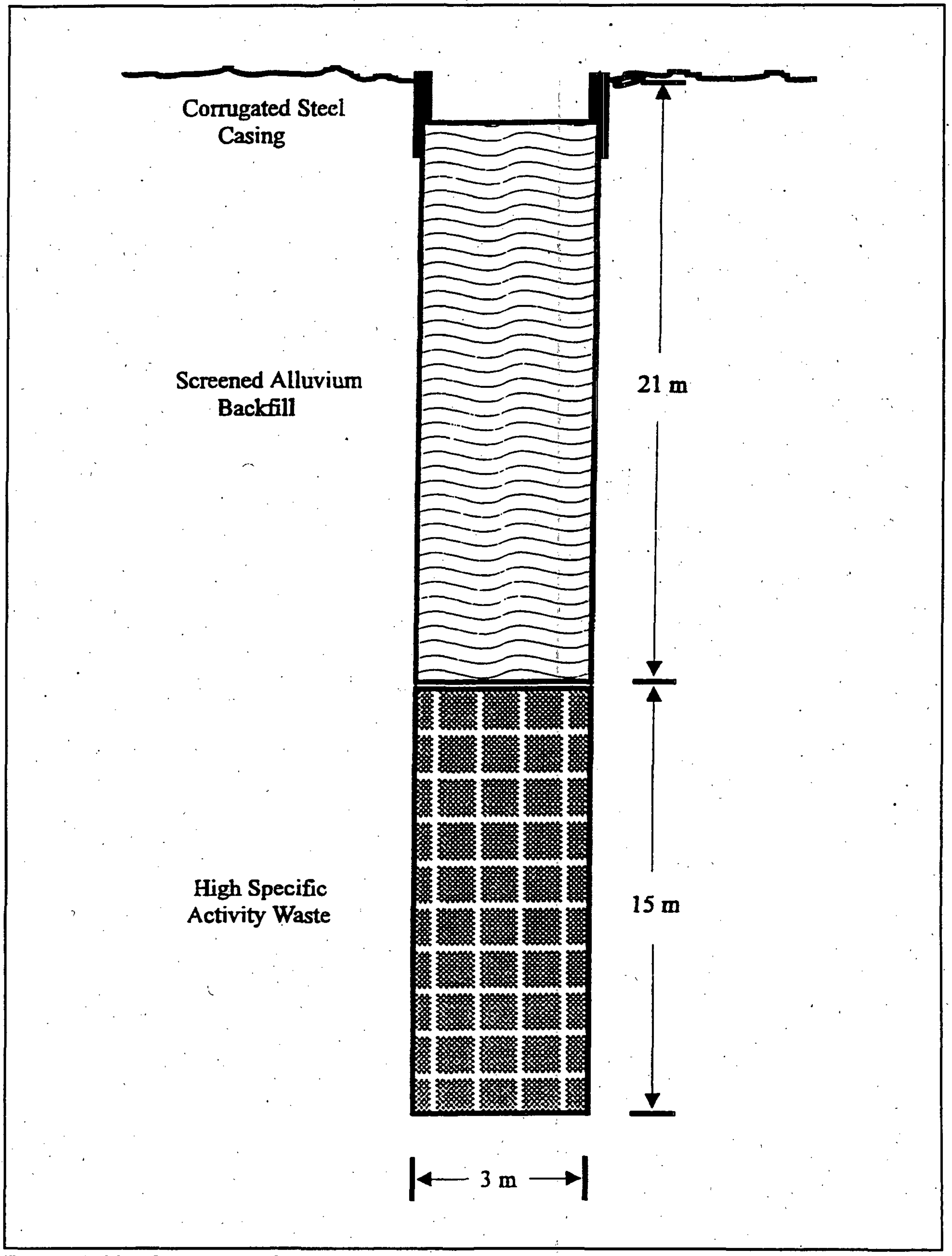


Figure 2.33 - Schematic of a GCD Cell.

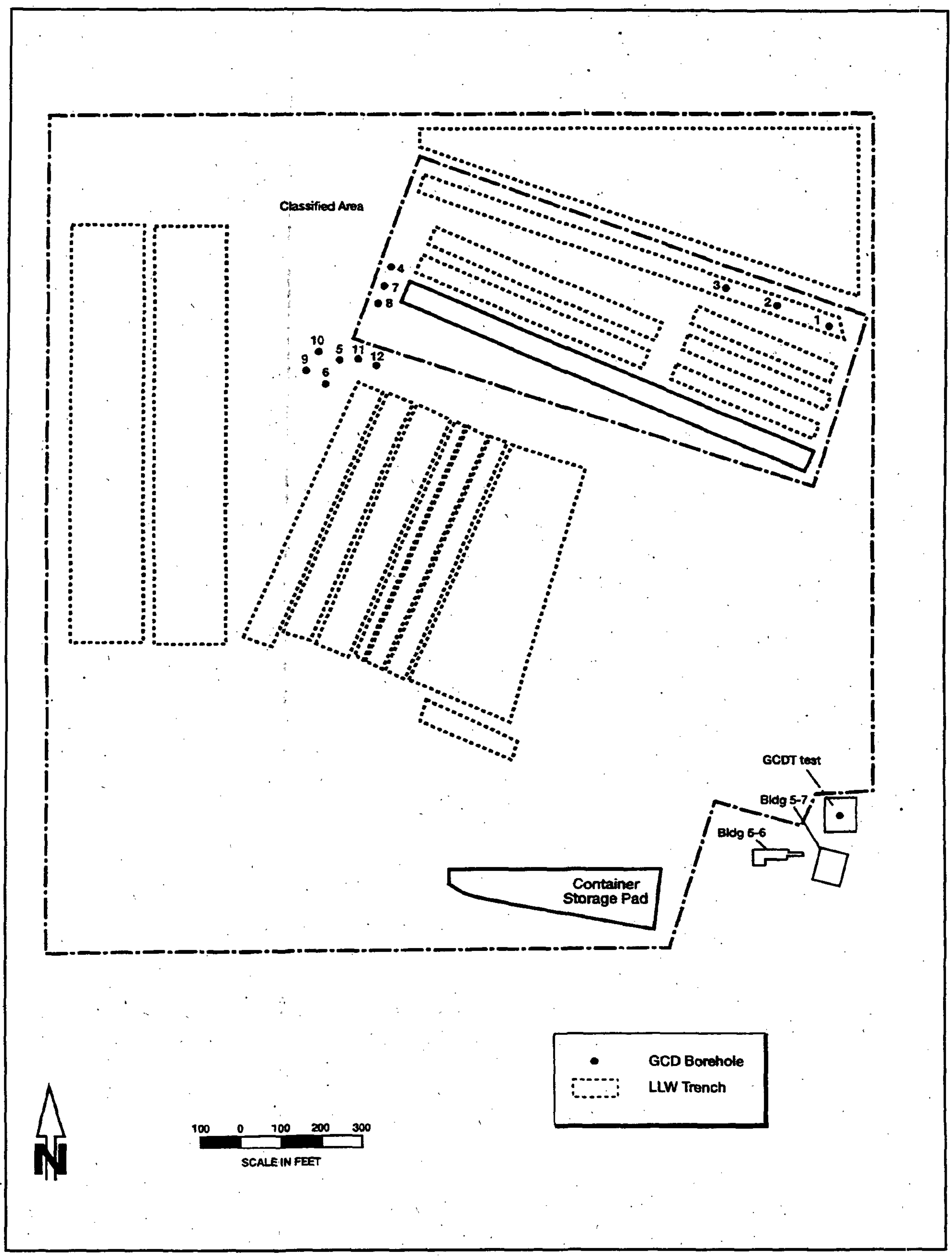


Figure 2.34 - Location of GCD boreholes in the LLWMU.

those wastes disposed of in boreholes 7C and 10U. The GCD program has been inactive since 1989, and is an issue currently being discussed by USDOE/NV and the state of Nevada.

Table 2.18. GCD boreholes at the Area 5 RWMS.

GCD Borehole	Disposal Area	Status
1	Classified	Closed, Full
2	Classified	Closed, Full
3	Classified	Closed, Full
4	Classified	Closed, Full
5	Unclassified	Closed, Full
6	Unclassified	Open, Full
7	Classified	Open, Full
8	Classified	Open, Empty
9	Unclassified	Open, Empty
10	Unclassified	Closed, Full
11	Unclassified	Open, Full
12	Unclassified	Open, Empty
GCDT	Unclassified	Closed, Full

2.9.3 Waste Storage

Three waste storage areas exist within or adjacent to the LLWMU. These are the Transuranic Waste Storage Pad, the Hazardous Waste Storage Unit, and the Mound Strategic Materials Storage Yard (Figure 2.32). The Transuranic Waste Storage Pad is a 0.8 ha asphalt pad used for the storage of 612 m^3 of mixed TRU waste. Final disposal of this TRU waste is awaiting licensing of the Waste Isolation Pilot Plant (WIPP) in New Mexico or another treatment, storage, or disposal unit. The Hazardous Waste Storage Unit (or Hazardous Waste Accumulation Site) is a concrete pad used for less than 90-day storage of hazardous waste. It is located across the 5-01 road from the LLWMU. The Mound Strategic Materials Storage Yard is located several kilometers north of the RWMS at the end of the 5-01 road. This site is used for the storage of uranium source material. The waste storage areas are not considered in the performance assessment.

2.9.4 Waste Characterization and Certification

Shipment and transfer of LLW to the Area 5 RWMS is controlled by USDOE/HQ and USDOE/NV. Generators seeking to dispose of waste at the NTS must first obtain written verification from USDOE/HQ that their waste is a defense waste. Approval to ship waste is granted by USDOE/NV after the generator documents and implements a waste characterization and waste certification plan that meets the requirements contained in NVO-325 (USDOE/NV, 1992). Generator waste characterization plans are designed to physically, chemically, and radiologically characterize waste and to document that waste meets waste acceptance criteria. Waste certification plans are prepared to ensure that waste is identified, segregated, characterized, and packaged in accordance with the requirements of NVO-325, and in a manner that is consistent with the American National Standards Institute/American Society of Mechanical Engineers (ANSI/ASME) NQA-1 requirements (ASME, 1989). Successful implementation of the waste certification and characterization plans is determined by field audits conducted by USDOE/NV. The field audit includes a traceability review designed to assess the effectiveness of the certification plan. To confirm the results of waste characterization plans, USDOE/NV may request that the generator perform additional sampling and analysis or request that split samples be sent to an independent laboratory. Waste generator programs are audited at the time of initial application and annually thereafter. Changes involving the Waste Certification Official, USDOE Field Office contacts, sampling and analysis plans, analytical laboratories, additions or changes to a waste stream, or changes requested by a regulatory agency require formal review by USDOE/NV. Significant changes require submission of a revised application and an additional field audit.

Generators may use a number of methods to perform radiological characterization of waste. Acceptable methodologies include use of materials accountability data, knowledge of the process and source, gross radiation measurements, and sampling and analysis. The concentrations of radionuclides not measured can be inferred from the concentrations of other radionuclides.

Generators may use process knowledge or sampling and analysis to determine if a LLW contains hazardous chemical constituents also. Use of process knowledge is permitted when it can be shown that it is physically difficult to sample the waste matrix, when sampling would violate the ALARA principle, or when the waste matrix is too heterogeneous to obtain a representative sample.

[illegible]

The approach used to prepare the performance assessment has been to assume the temporary closure cover is still present at site closure. This cap is a 2.4-m layer of screened native alluvium that extends 1.2 m above existing grade. Cap designs and closure plans prepared by the Integrated Closure Program are likely to enhance performance in the near term. Some aspects of cap performance may degrade over longer time periods, but the overall thickness is not expected to change significantly. Since cap thickness is the primary feature considered in the performance assessment, completion of a cap design is not expected to require immediate revision of the performance assessment. However, performance assessment revisions prepared after final cap closure plans are available should include these plans.

2.10 AREA 5 RWMS SITE INVENTORY

This section describes the radioactive materials inventory for the Area 5 RWMS and the final inventory used for the performance assessment. As noted previously, the NTS has disposed of wastes at the Area 5 RWMS since 1961. The inventory described here is limited to those shipments received from FY89 to FY93. At the time of preparation, FY93 was the last year that complete data were available. These data are organized in the database by fiscal year. These data are organized throughout this section by fiscal year also.

Generators wishing to ship waste to the NTS for disposal must submit an application to USDOE/NV for review and approval. Waste generator applications include a description of all proposed waste streams. Waste stream information submitted in the waste generator application often is estimated since the waste may not have been generated or packaged at the time of application. Information provided in the applications includes a brief physical description of the bulk matrix and the processes of generation and an estimate of the low, mean, and high activity concentration of significant radionuclides. Approval is granted on a waste stream-specific basis.

After receiving written approval from USDOE/NV, generators may transfer their waste to the Area 5 RWMS. Waste characterization data is reported to the site operator for entry into the site inventory at the time of shipment. These data are transmitted electronically in most instances. Fifteen generators have transferred waste to the Area 5 RWMS since the beginning of FY89 (Table 2.19), of which 11 are currently approved (Table 2.20).

Table 2.19. Generators that shipped LLW to the Area 5 RWMS from October 1, 1988 through September 30, 1993 and their abbreviations used in this report.

Aberdeen Proving Grounds, Aberdeen, MD, Department of Defense (USAA)
Fernald Environmental Restoration Management Company, Fernald, OH (FERMCO)
General Atomics, San Diego, CA (GA)
Inhalation Toxicology Research Institute, Albuquerque, NM (ITRI)
Lawrence Livermore National Laboratory, Livermore, CA (LLNL-CA)
Mound Facility, Miamisburg, OH, EG&G Mound Applied Technologies (Mound)
NTS, Mercury, NV, Defense Nuclear Agency (DNA)
NTS, Mercury, NV, Lawrence Livermore National Laboratory (LLNL-NTS)
NTS, Mercury, NV, Los Alamos National Laboratory (LANL-NTS)
NTS, Mercury, NV, Reynolds Electrical & Engineering Company (REECo)
Pantex Plant, Amarillo, TX (Pantex)
Rocketdyne Division, Canoga Park, CA, Rockwell (Rocketdyne)
Rocky Flats Plant, Golden, CO, EG&G Rocky Flats (RFP)

After September 30, 1992, a new database, known as the LLW Information System (LLWIS), became operational. Data in the LLWIS are stored in a single record, indexed by package. LLWIS data fields are listed in Table 2.22.

Table 2.21. Summary of data fields for pre-FY92 database records.

Record Indexed by Shipment Number	
Shipment Number	
Generator Identification Code	
Date of Arrival at the RWMS	
Burial Site (Area 3 or 5)	
Site of Generation (NTS, Offsite)	
Operation Type (B-burial, G-generation, R-retrievable)	
External Volume (includes package dimensions)	
Gross Weight (includes weight of package and waste)	
Nuclide	
Nuclide Activity	(Ci)
Waste Code	(Biological Waste, Contaminated Equipment, Decontamination Debris, Dry Solid, Solidified Sludge, Non-classified)
Nuclide Category	(Transuranic, Uranium/Thorium, Fission Products, Induced Activity, Tritium, Alpha, Other)
Number of Drums in the Shipment	
Number of Boxes in the Shipment	
Number of Nonstandard Boxes in the Shipment	
Record Indexed by Package Number	
Package Identification Code	
Disposal Date	
Container Type (B - box, D - drum, N - nonstandard)	
Disposal Location	
Alpha (identifies the alpha coordinate for the package)	
Numeric (identifies the numeric coordinate for the package)	
Tier (identifies the tier level of disposal)	

Table 2.22. Summary of data fields for post-FY92 database records.

Package Identification Code (8 characters, shipment number plus a 6 character package no.)
Waste Stream Identification Code
Arrival Date
Burial Site (Area 5 or Area 3)
Generation Site (NTS, Offsite)
Operation Type (B-burial, G-generation, R-retrievable)
Package Completed Date
Activity Assay Date
Container Code (identifies the type of the waste package)
External Volume (m^3)
Internal Volume (m^3)
Gross Weight (kg)
Net Weight (kg)
Nuclide
Nuclide Activity
Waste Code
Nuclide Category
Disposal Date
Disposal Location

The inventory used in the performance assessment is based on queries of the existing waste management databases. Since important data fields in the pre-FY92 database (activity, volume, and mass) are grouped by shipment, inaccurate or inconsistent results can be obtained for some queries. These problems arise because these data are grouped by shipment rather than by package. Problems with the pre-FY92 records occur if packages from a single shipment were disposed at multiple locations or on multiple dates. This could cause double, or multiple, counting of some packages. Instances where shipments might have been split are believed to be rare. The post-FY92 database (LLWIS) does not have these potential problems.

Generator waste characterization methods and reporting methods have caused additional problems with database records. In some instances generators have used codes for radionuclide mixtures. Codes used previously include MFP (mixed fission products), Pu-52 (weapons grade plutonium), D-238 (depleted uranium), and enriched uranium. Mixture codes found in the database have been replaced with the activities of specific isotopes for the performance assessment. The details of these corrections are described below. In addition, review of the inventory suggests that characterization data are incomplete. For example, the isotope ratios reported by some generators are inconsistent with expected values, suggesting that possibly important isotopes were not reported. These data must be evaluated on a per-generator basis or even a per-waste stream basis because of the many processes represented by NTS generators. These issues and their resolutions are also described below.

2.10.1 Preliminary Inventory

A preliminary inventory was developed based on unrevised database records. This inventory includes all waste disposed of from October 1, 1988 through September 30, 1993. It includes all waste types (classified LLW, unclassified LLW, MW) and all disposal units (pits, trenches, GCD). Fifteen generators have shipped waste to the Area 5 RWMS during this interval (Table 2.19).

As of March, 14, 1994, there were eleven generators approved to ship waste to the NTS (Table 2.20). Thirteen additional sites have been identified as potential generators, including five which have reached the review and audit stage (Table 2.23).

Table 2.23. USDOE facilities identified as potential NTS generators.

Kansas City Plant, Kansas City, MO, Allied Signal
Mound Facility, Miamisburg, OH, EG&G Mound Applied Technologies
Pinellas Plant, Pinellas Co., FL
Rocketdyne Division, Canoga Park, CA, Rockwell
Sandia National Laboratory, Albuquerque, NM
Battelle Memorial Institute, Columbus, OH
Idaho National Engineering Laboratory, Idaho Falls, ID
Johnston Atoll, Defense Nuclear Agency
Los Alamos National Laboratory, Los Alamos, NM
Paducah Gaseous Diffusion Plant, Paducah, KY, Martin Marietta Energy Systems
Portsmouth Gaseous Diffusion Plant, Portsmouth, OH, Martin Marietta Energy Systems
Oak Ridge Reservation, Oak Ridge, TN
U.S. Army Defense Consolidation Facility

The total activity of unclassified low-level and mixed wastes disposed of by shallow land burial are listed by fiscal year (FY) in Table 2.24. The unclassified shallow land burial inventory represents over 60 percent of the total activity and accounts for nearly all of the activity of many radionuclides. The classified shallow land burial inventory is presented in

Table 2.25. In comparison, the classified wastes disposed of by shallow land burial account for only 1.2 percent of the site inventory and are limited to ^{3}H, ^{60}Co, ^{90}Sr and ^{238}U. Classified and unclassified GCD boreholes received waste in FY89 and FY90. Only two radionuclides were reported, ^{3}H and ^{238}U. However, the GCD ^{3}H disposal was a significant fraction (37 percent) of the total site inventory. The GCD inventory is presented in Table 2.26.

Table 2.24. Unrevised unclassified shallow land burial radionuclide inventory in Curies for FY89 through FY93.

Table 2.24. continued.

Radionuclide	FY89	FY90	FY91	FY92	FY93	Total (Ci)
^{59}Fe		9.5×10^{-6}			0.040	0.040
^{67}Ga				5.0×10^{-5}	2.0×10^{-9}	5.0×10^{-5}
^{3}H	1.7×10^{4}	1.7×10^{4}		1.4	2.8×10^{4}	6.2×10^{4}
^{125}I					6.0×10^{-4}	6.0×10^{-4}
^{131}I					0.0050	0.0050
^{133}I					0.0097	0.0097
^{85}Kr		9.0×10^{-5}			0.0081	0.0082
^{140}La					0.0045	0.0045
MFP	0.15	0.079				0.23
^{54}Mn		2.1×10^{-4}			0.030	0.030
^{22}Na	0.050	1.0×10^{-5}			2.8×10^{-6}	0.050
^{95}Nb		7.9×10^{-4}			0.020	0.021
^{59}Ni	3.0×10^{-6}					3.0×10^{-6}
^{63}Ni	1.8×10^{-4}			0.51	0.038	0.54
^{237}Np	0.0010					0.0010
^{32}P	0.081	0.011			0.0039	0.096
^{231}Pa		0.0063				0.0063
^{210}Po	1.0×10^{-6}					1.0×10^{-6}
^{147}Pm	1.0×10^{-5}			1.0	0.0041	1.0
^{210}Pb	1.0×10^{-6}	2.5×10^{-4}			8.6×10^{-4}	0.0011

Table 2.24. continued.

Table 2.25. continued.						
Radionuclide	FY89	FY90	FY91	FY92	FY93	Total
^{238}U	46	14		22	22	103
Total	47	50		23	1.1×10^{3}	1.2×10^{3}

Table 2.26. Unrevised classified and unclassified GCD radionuclide inventory in Curies for FY89 through FY93.

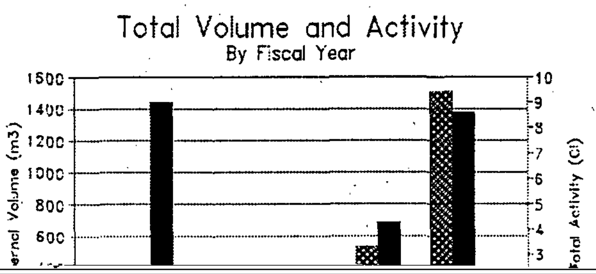
Radionuclide	FY89	FY90	FY91	FY92	FY93	Total (Ci)
^{3}H		3.8×10^{3}				3.8×10^{3}
^{238}U	1.9					1.9
Total	1.9	3.8×10^{3}				3.8×10^{3}

Major generators active at any time during FY89 to FY93 are profiled in (Figures 2.35 through 2.44). Three generators (RFP, FERMCO and Mound) account for 88 percent of total volume received (Figures 2.39, 2.41, 2.44). Three generators (LLNL-CA, SNL-CA, and Mound) account for greater than 99 percent of the activity received (Figures 2.37, 2.42, 2.44). These three generators produce the high-specific activity tritium waste streams that contribute the greatest activity to the total inventory.

Past and current NTS waste generators are or were involved in the design, assembly, or testing of nuclear weapons. Most are no longer actively involved in production. Waste streams from these inactive sites are derived from environmental restoration projects or decontaminating and decommissioning (D&D). These waste streams are usually contaminated with a few nuclides formerly used at the site. Most elements of the USDOE production cycle are represented among NTS generators, with the exception of fuel reprocessing. NTS generators handle a small number of relatively pure isotopes used in nuclear weapons. The predominate nuclides are ^{3}H and isotopes of uranium, thorium, and plutonium. Waste streams containing actinides are the most important in terms of volume and ^{3}H waste streams are most important in terms of activity (Table 2.27). Several NTS generators are research laboratories that generate waste streams with numerous radionuclides. These waste streams, however, tend to have radionuclide sources that are well characterized, isotopically pure, and low in activity concentration. Table 2.28 shows a break down of the inventory by radionuclide categories as reported by generators. According to generators' reports, only 3×10^{-4} percent of the total activity shipped was associated with mixed fission product waste streams. Based on inventory records, ^{90}Sr and ^{137}Cs account for approximately 0.002 percent of the total activity, or slightly less than 2 Ci. Waste streams containing fission products and activation products originate predominately from research laboratories at Lawrence Livermore National Laboratory (Figure 2.37), the Inhalation and Toxicology Research Institute (Figure 2.36), and Sandia National Laboratory (Figure 2.42). Fission products and activation products in these waste streams are predominately from isotopically pure sources. Less than 1 Ci of the total ^{90}Sr and ^{137}Cs activity is suspected to be associated with mixed fission products. Generators producing waste streams with mixed fission products are LLNL-CA, Rocketdyne, and NTS-based generators.

Figure 2.35. General Atomics waste stream profile for FY89 through FY93.

Generator Profile: General Atomics		
	Total Disposed by Generator FY89 to FY93	Total Disposed as a Percent of Total Site Inventory
Volume (m^3)	2,059	4.4 %
Activity (Ci)	21.9	0.02 %
Major Nuclides in the Generator's Waste Stream		
^{234}U	21 Ci	30.6 %
^{235}U	0.69 Ci	17.8 %



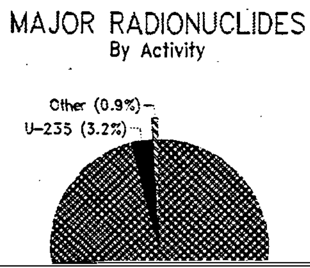
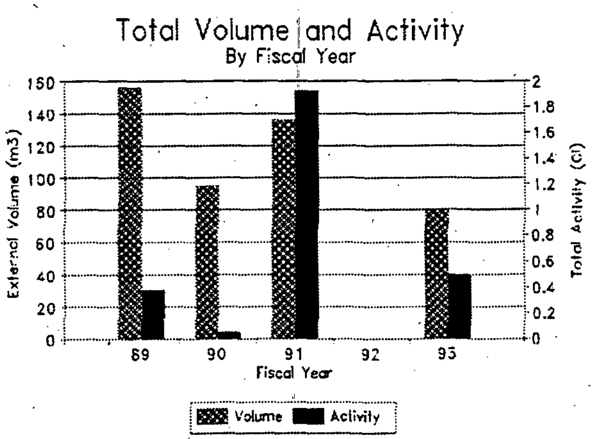


Figure 2.36. Inhalation Toxicology Research Institute waste stream profile for FY89 through FY93.

Generator Profile: Inhalation Toxicology Research Institute		
	Total Disposed by Generator FY89 to FY93	Total Disposed as a Percent of Total Site Inventory
Volume (m^3)	467	0.99 %
Activity (Ci)	2.86	0.003 %
Major Nuclides in the Generator's Waste Stream		
^{3}H	0.58 Ci	6×10^{-4} %
^{137}Cs	0.56 Ci	56.5 %
^{63}Ni	0.54 Ci	99.7 %
^{14}C	0.53 Ci	99.6 %
^{90}Sr	0.45 Ci	46.9 %
^{244}Cm	0.15 Ci	99.8 %
Nuclides Contributing Significantly to the Total Site Inventory		
^{232}U	0.015 Ci	100 %
^{243}Cm	0.0005 Ci	100 %
^{243}Am	0.0001 Ci	90.9 %
^{226}Ra	0.0068 Ci	61.8 %
^{36}Cl	2.0×10^{-8} Ci	100 %
^{207}Bi	2.0×10^{-9} Ci	100 %
^{133}Ba	5.3×10^{-5} Ci	100 %



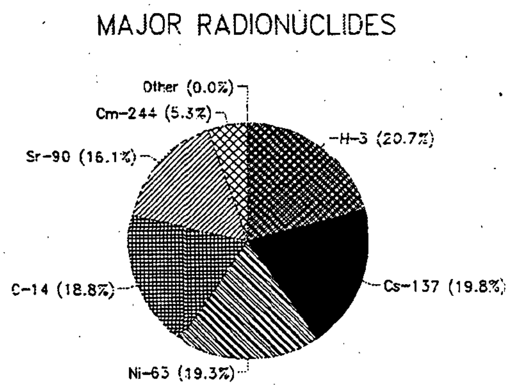
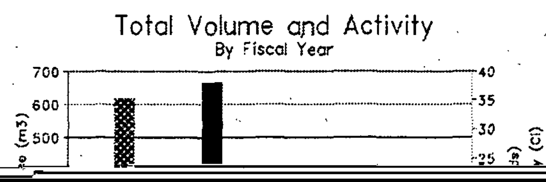


Figure 2.37. Lawrence Livermore National Laboratory waste stream profile for FY89 through FY93.

Generator Profile: Lawrence Livermore National Laboratory		
	Total Disposed by Generator FY89 to FY93	Total Disposed as a Percent of Total Site Inventory
Volume (m^3)	951	2.0 %
Activity (Ci)	46,938	46.3 %
Major Nuclides in the Generator's Waste Stream		
^{3}H	46,933 Ci	46.4 %
Nuclides Contributing Significantly to the Total Site Inventory		
^{59}Ni	3×10^{-6} Ci	100 %
^{90}Sr	0.21 Ci	22.0 %
^{93}Zr	4×10^{-6} Ci	76.8 %
^{99}Tc	5×10^{-5} Ci	75.5 %
^{107}Pd	1×10^{-6} Ci	74.0 %
^{126}Sn	1×10^{-6} Ci	76.1 %
^{129}I	3×10^{-7} Ci	76.7 %
^{135}Cs	5×10^{-6} Ci	77.7 %
^{137}Cs	0.31 Ci	31.7 %
^{151}Sm	0.016 Ci	78.9 %
^{233}U	6×10^{-6} Ci	37.4 %
^{242}Cm	2×10^{-8} Ci	100 %
^{252}Cf	1×10^{-5} Ci	99.8 %



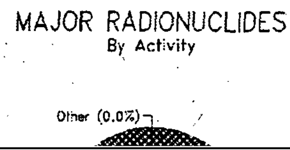
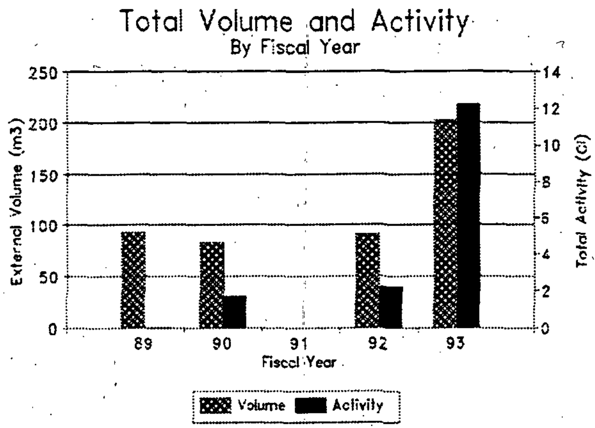


Figure 2.38. Pantex waste stream profile for FY89 through FY93.

Generator Profile: Pantex		
	Total Disposed by Generator FY89 to FY93	Total Disposed as a Percent of Total Site Inventory
Volume (m^3)	469	1.0 %
Activity (Ci)	16.2	0.02 %
Major Nuclides in the Generator's Waste Stream		
^{3}H	15 Ci	0.01 %
^{238}U	1.1 Ci	0.9 %



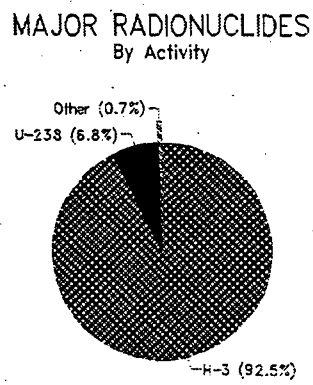
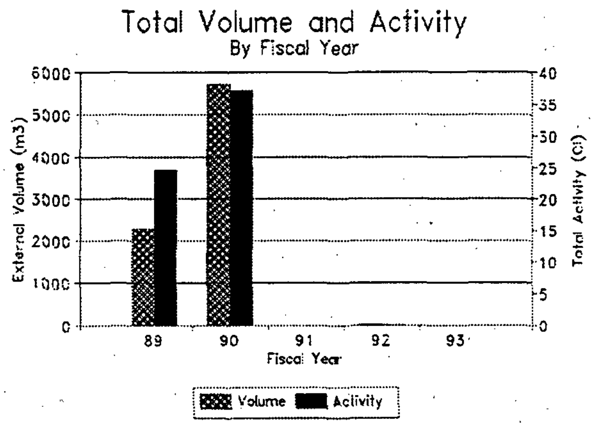


Figure 2.39. Rocky Flats Plant waste stream profile for FY89 through FY93.

Generator Profile: Rocky Flats Plant		
	Total Disposed by Generator FY89 to FY93	Total Disposed as a Percent of Total Site Inventory
Volume (m^3)	8,018	17.0 %
Activity (Ci)	61.9	0.06 %
Major Nuclides in the Generator's Waste Stream		
^{234}U	6.3 Ci	9.1 %
^{238}U	1.9 Ci	1.5 %
^{239}Pu	14.0 Ci	92.0 %
^{240}Pu	3.2 Ci	99.6 %
^{241}Pu	34.1 Ci	97.1 %
^{241}Am	1.8 Ci	98.3 %
Nuclides Contributing Significantly to the Total Site Inventory		
^{242}Pu	3×10^{-4} Ci	91.7 %



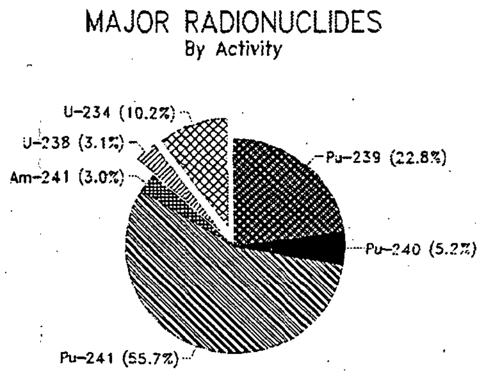
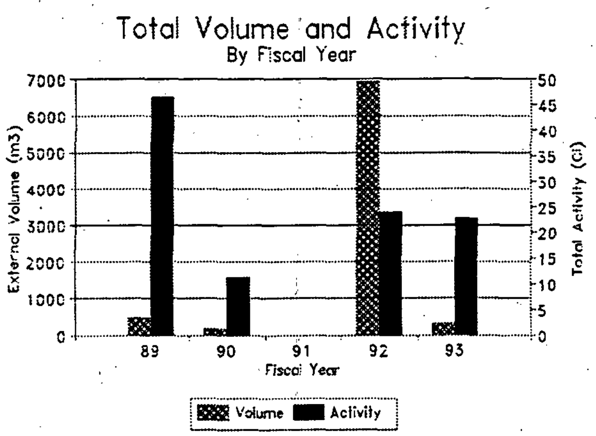


Figure 2.40. Aberdeen Proving Grounds waste stream profile for FY89 through FY93.

Generator Profile: Aberdeen Proving Grounds		
	Total Disposed by Generator FY89 to FY93	Total Disposed as a Percent of Total Site Inventory
Volume (m^3)	1,266	2.7 %
Activity (Ci)	105	0.1 %
Major Nuclides in the Generator's Waste Stream		
^{234}U	8.7 Ci	12.7 %
^{235}U	1.5 Ci	39.1 %
^{238}U	94 Ci	72.7 %



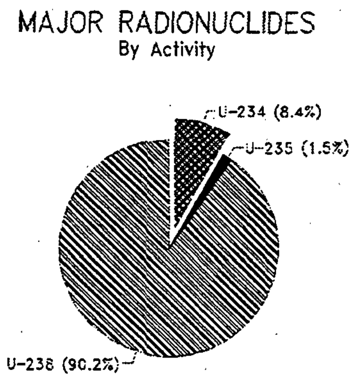
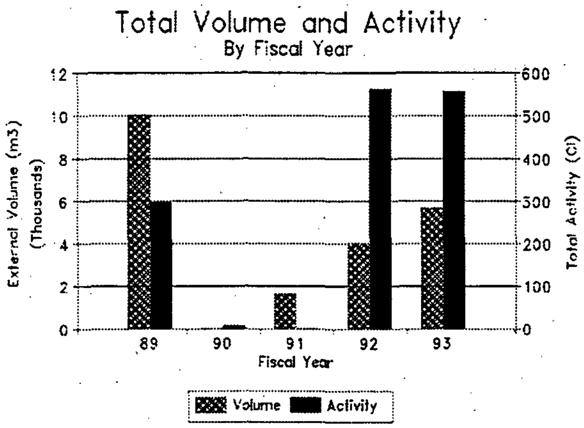


Figure 2.41. Fernald Environmental Restoration Management Company waste stream profile for FY89 through FY93.

Generator Profile: Fernald Environmental Restoration Management Company		
	Total Disposed by Generator FY89 to FY93	Total Disposed as a Percent of Total Site Inventory
Volume (m^3)	23,393	49.6 %
Activity (Ci)	94	0.09 %
Major Nuclides in the Generator's Waste Stream		
^{230}Th	2.8 Ci	99.7 %
^{234}U	31 Ci	45.3 %
^{235}U	1.3 Ci	33.2 %
^{238}U	25 Ci	19.3 %
^{232}Th	18 Ci	99.5 %



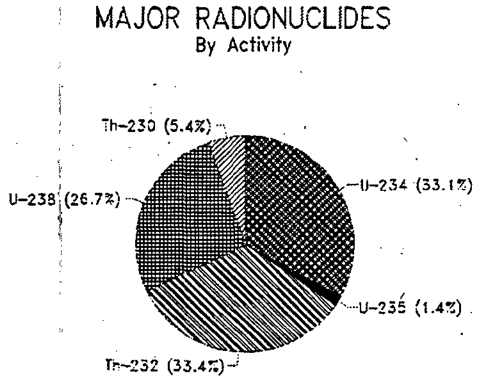
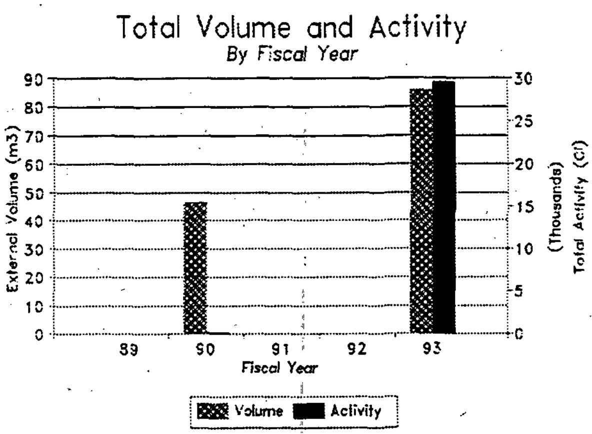


Figure 2.42. Sandia National Laboratory waste stream profile for FY89 through FY93.

Generator Profile: Sandia National Laboratory, California		
	Total Disposed by Generator *FY89 to FY93*	Total Disposed as a Percent of Total Site Inventory
Volume (m^3)	132	0.3 %
Activity (Ci)	29,652	29.3 %
Major Nuclides in the Generator's Waste Stream		
^{3}H	29,650 Ci	29.3 %
Nuclides Contributing Significantly to the Total Site Inventory		
^{60}Co	0.12 Ci	86.7 %
^{90}Sr	0.24 Ci	24.7 %



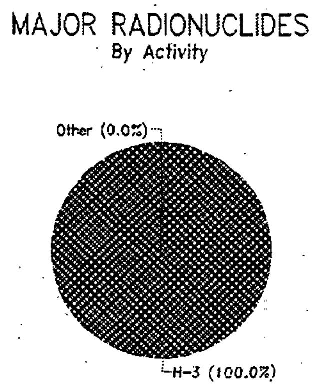
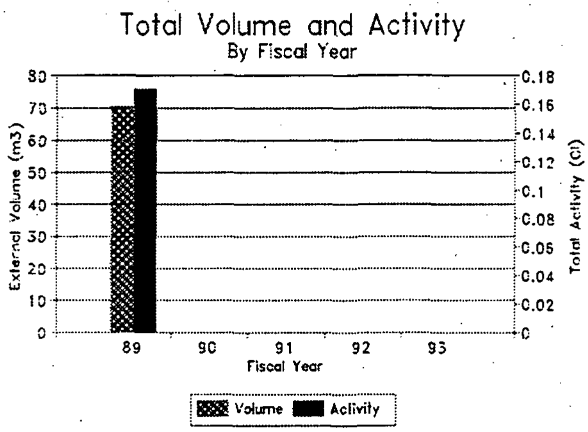


Figure 2.43. Rocketdyne waste stream profile for FY89 through FY93.

Generator Profile: Rocketdyne Division, Rockwell		
	Total Disposed by Generator FY89 to FY93	Total Disposed as a Percent of Total Site Inventory
Volume (m^3)	70	0.15 %
Activity (Ci)	0.17	2×10^{-4} %
Major Nuclides in the Generator's Waste Stream		
^{137}Cs	0.10 Ci	10.6 %
^{90}Sr	0.053 Ci	5.5 %
^{60}Co	0.007 Ci	4.9 %



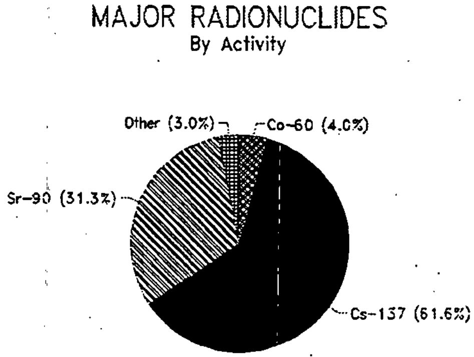


Figure 2.44. Mound waste stream profile for FY89 through FY93.

Generator Profile: Mound Facility		
	Total Disposed by Generator FY89 to FY93	Total Disposed as a Percent of Total Site Inventory
Volume (m³)	[illegible]	[illegible]

Table 2.27 and 2.28. Total volume and activity by nuclide category and waste code of unclassified and classified LLW disposed at the Area 5 RWMS from FY89 to FY93.

	Transuranic	Uranium/ Thorium	Fission Products	Induced Activity	Tritium	Alpha	Other	Total
Total Volume (m^3)	0.0	26,900	143	5.68	2,400	17,100	604	47,200
% of Total Volume	0.0	57.1	0.3	0.012	5.1	36.2	1.3	
Total Activity (Ci)	0.0	234	0.275	0.0815	100,300	749	9.62	101,290
% of Total Activity	0.0	0.2	3×10^{-4}	8×10^{-5}	99	0.7	0.009	

Table 2.28. Total volume and activity by waste code of unclassified and classified LLW disposed of at the Area 5 RWMS from FY89 to FY93.

From FY89 through FY93, the Area 5 RWMS received 47,200 m^3 of waste. Approximately 93 percent of the volume was associated with actinide-bearing waste streams (Table 2.27). Waste streams received over this period are predominantly (61 percent) heterogenous mixtures of contaminated debris and equipment (Table 2.28). These waste streams include such materials as laboratory equipment, industrial equipment, building materials, soil, personal protective equipment, furniture, weapons components, and spent radionuclide containers or generators (e.g. gas cylinders, ion exchange resins, adsorption beds).

2.10.2 Inventory Revisions

The raw inventory records, as summarized in Table 2.24, 2.25, and 2.26, were revised before being used in the performance assessment. First, all nuclides with half-lives less than five years that decay to a stable progeny were deleted from the inventory. These nuclides will decay to negligible levels during the 100-year period of institutional control. The nuclides appearing on the inventory that were deleted for this reason include: ^{7}Be, ^{22}Na, ^{32}P, [redacted] ^{110m}Ag, ^{124}Sb, ^{125}Sb, ^{125}I, ^{131}I, ^{133}I, ^{134}Cs, ^{136}Cs, ^{141}Ce, ^{140}Ba, ^{140}La, ^{144}Ce, ^{155}Eu, ^{169}Yb, and ^{182}Ta. Next, any members of a serial decay chain with a half-life less than five years and a supporting parent present with a half-life greater than five years were deleted. These nuclides will reach secular or transient equilibrium during the 100-year period of institutional control. These nuclides included: ^{210}Po, ^{224}Ra, ^{220}Rn, ^{222}Rn, and ^{228}Th. Finally,

[redacted]

corrected based on original shipping records. The special case thorium waste activity was removed from the shallow land burial inventory (Table 2.29). This special case thorium waste inventory will be analyzed as a separate source term.

Table 2.29. Inventory of thorium special case waste received for disposal in Pit 6 (PO6U).

Radionuclide	Special Case Waste Inventory (Ci)	External Volume (m^3)
^{232}Th	18.2	368
^{230}Th	2.82	

Past use of isotope codes is a source of error in database records. Two codes appear in inventory records since 1988: MFP (mixed fission products) and Pu-52 (weapons grade Pu).

In 1989 and 1990, the Rocky Flats Plant used the waste code Pu-52 to describe weapons grade plutonium scrap in their waste streams. The Pu-52 activities received were 32.8 Ci in

SA_i = specific activity of ith plutonium isotope,

SA_{52} = specific activity of Pu-52

SA_{52}	=	specific activity of Pu-52,
λ_1	=	decay constant of ^{241}Pu,
λ_2	=	decay constant of ^{241}Am, and
t	=	elapsed time between last separation and disposal (20 years).

This method yields an ^{241}Am estimate of 1.81 Ci. Overall, the isotopic ratios estimated above for Pu-52 are in reasonable agreement with the ratios reported by the Rocky Flats Plant for shipments delivered in FY92, the only year that the Rocky Flats Plant reported the activities of specific isotopes.

The isotope code MFP was used by three generators in FY89 and FY90 (Table 2.31). MFP was used to identify mixed fission products. Lawrence Livermore National Laboratory (LLNL) generated 95.7 percent of the total activity of MFP (0.231 Ci). LLNL reported that the waste stream contained fission products from fast neutron fission of ^{239}Pu during nuclear weapons tests. Although the other two waste streams are minor sources, they too are believed to originate from nuclear testing.

Table 2.31. Generators using the MFP (mixed fission product) code and the activity

due to the complexities of estimating their activity and the relatively small contribution of MFP activity to the total fission product and activation product inventory. Chemical fractionation was also ignored.

Table 2.32. Estimated disposal of fission products from waste streams using the MFP code.

Radionuclide	Half-life (yr)	Cumulative Yield From Fission of ^{239}Pu	Activity of Fission Products for 0.231 Ci of MFP (Ci)	Mean Annual Disposal Rate (Ci yr^{-1})
^{79}Se	6.5×10^4	6.55×10^{-4}	7.5×10^{-7}	1.5×10^{-7}
^{87}Rb	4.7×10^{10}	0.0212	3.3×10^{-11}	6.7×10^{-12}
^{90}Sr	28.6	0.0214	0.055	0.011
^{93}Zr	1.5×10^6	0.0333	1.6×10^{-6}	3.2×10^{-7}
^{99}Tc	2.1×10^5	0.0610	2.1×10^{-5}	4.2×10^{-6}
^{107}Pd	6.5×10^6	0.0395	4.5×10^{-7}	9.0×10^{-8}
^{126}Sn	1.0×10^5	7.51×10^{-4}	5.6×10^{-7}	1.1×10^{-7}
^{129}I	1.6×10^7	0.0298	1.4×10^{-7}	2.8×10^{-8}
^{135}Cs	2.3×10^6	0.0656	2.1×10^{-6}	4.2×10^{-7}
^{137}Cs	30.17	0.0679	0.17	0.034
^{151}Sm	90	0.0088	0.0072	0.0014

The activity of fission products in MFP was calculated as:

$$A_i = A_T \frac{\lambda_i Y_i}{\sum_{j=1}^{n} \lambda_j Y_j} \tag{2.16}$$

where:

A_i = activity of the ith fission product,
A_T = total MFP activity,
λ_i = radioactive decay constant of ith fission product,
Y_i = cumulative fission yield of ith fission isobar, and
n = number of fission chains.

Estimated activities of fission products in MFP shipments received since FY88 are presented in Table 2.32. In relative terms, the activity from MFP shipments represents a significant fraction of the total fission product inventory. However, the total fission product inventory at the Area 5 RWMS is small and in absolute terms the total activity from MFP is insignificant. The significance of the fission product revisions can be assessed by examining the estimated total inventories. The final site fission product inventory can be estimated as the mean disposal rate times the period of operation, 39 years. For two fission products, ^{79}Se and ^{87}Rb, the predicted total inventory is less than the activity that would deliver a CEDE of 25 mrem if the entire inventory were inhaled or ingested by an individual. For this reason, these two nuclides were not added to the inventory. The remaining radionuclides

Table 2.33. Major generators of ^{90}Sr and ^{137}Cs and the source of radionuclides in their waste streams.

Table 2.34. Estimated disposal of minor fission products potentially present in LLNL-CA and Rocketdyne waste streams containing ^{90}Sr and ^{137}Cs.

Radionuclide	Half-life (yr)	Cumulative Yield From Fission of ^{239}Pu	Activity of Fission Products for 0.463 Ci of ^{90}Sr + ^{137}Cs (Ci)	Mean Annual Disposal Rate (Ci yr^{-1})
^{79}Se	6.5×10^{4}	6.55×10^{-4}	1.5×10^{-6}	3.0×10^{-7}
^{87}Rb	4.7×10^{10}	0.0212	6.7×10^{-11}	1.3×10^{-11}
^{90}Sr	28.6	0.0214	Not Revised	Not Revised
^{93}Zr	1.5×10^{6}	0.0333	3.2×10^{-6}	6.4×10^{-7}
^{99}Tc	2.1×10^{5}	0.0610	4.3×10^{-5}	8.5×10^{-6}
^{107}Pd	6.5×10^{6}	0.0395	9.1×10^{-7}	1.8×10^{-7}
^{126}Sn	1.0×10^{5}	7.51×10^{-4}	1.1×10^{-6}	2.2×10^{-7}
^{129}I	1.6×10^{7}	0.0298	2.8×10^{-7}	5.6×10^{-8}
^{135}Cs	2.3×10^{6}	0.0679	1.0×10^{-5} †	2.0×10^{-6}
^{137}Cs	30.17	0.0683	Not Revised	Not Revised
^{151}Sm	90	0.0088	0.014	0.0029

† - ^{135}Cs activity estimated as a fraction of the total ^{137}Cs activity.

In conclusion, revisions applied to the inventory for the waste code MFP and unreported fission products are uncertain. Since 1988, unseparated fission products have been a very minor component of waste streams disposed of at the Area 5 RWMS. Conservative estimates of the activities present are extremely low, generally less than a few microcuries. Those nuclides with potential for any significant impact on site performance have been conservatively added to the inventory.

Inventory records and generator shipping papers suggest that there are problems with the recorded activities of uranium isotopes. Inventory records summarized by generators and by fiscal years show that generators often report only one or two naturally occurring uranium isotopes when at least three are expected (Table 2.35). Descriptions, such as depleted uranium, enriched uranium, and the codes DU and D-238, may have been used in the past. To correct for unreported uranium isotopes, generator applications were reviewed and in some instances generators were contacted to determine if a single uranium isotopic mixture could be assumed. In cases where uncertainty existed about uranium isotopic ratios, the final isotopic ratio selected represented the best estimate available. Corrections were performed using the relation:

$$A_E = \frac{A_r\, f_E\, SA_E}{f_r\, SA_r} \tag{2.18}$$

where:

A_E	=	estimated activity of the unreported isotope,
A_r	=	reported activity of the reference isotope,
f_E	=	isotope mass fraction of the unreported isotope,
f_r	=	isotope mass fraction of the reference isotope,
SA_E	=	specific activity of the unreported isotope, and
S_r	=	specific activity of the reference isotope.

No corrections were made when generators reported all three natural isotopes as the records for these shipments were assumed correct.

Three generators (Pantex, SNL, and USAA) have reported only ^{238}U in their waste streams. Review of the generator applications indicated that these waste streams contained depleted uranium only. Additional ^{235}U and ^{234}U were added to the inventory using the reported ^{238}U activity as the reference and an assumed isotopic mixture for depleted uranium (Table 2.35). Five generators reported only ^{238}U and ^{235}U. Among these, three generators (RFP, LLNL and GA) processed various isotopic mixtures. RFP, LLNL, and GA records were revised assuming that all the ^{238}U reported was depleted uranium and that all the ^{235}U reported was enriched uranium. Actual uranium enrichments used were based on generator applications and reports. ITRI records were not modified due to the small activity involved. FERMCO reported ^{238}U and ^{235}U in FY89 and FY90 and reported all three natural isotopes in subsequent years. Since FERMCO has processed many forms of uranium, the mean isotopic fractions from FY91 to FY93 and the reported ^{238}U activity were used to estimate the ^{234}U received in FY89 and FY90. A single generator (Mound) reported ^{238}U and ^{234}U in equal activities. These shipments were assumed to be natural uranium and ^{235}U was added as appropriate. These corrections have a significant effect on the inventory of ^{235}U and ^{234}U. Uranium-235 increases by 78 percent due largely to traces of the isotope in large quantities of depleted uranium. The ^{234}U inventory increases by 231 percent. This is attributable to large quantities of depleted uranium and small quantities of highly enriched uranium. These

Table 2.35. Uranium isotopes reported by generators each fiscal year and revisions made to the inventory.

Generator	Recorded Inventory (Ci)	Assumed Isotopic Mixture	Assumed Isotopic Mass Fractions	Estimated Revisions to Uranium Inventory

Table 2.35. continued.

Generator	Recorded Inventory (Ci)			Assumed Isotopic Mixture	Assumed Isotopic Mass Fraction				Estimated Revisions to Uranium Inventory			
	^{238}U	^{235}U	^{234}U		^{238}U	^{235}U	^{234}U	^{236}U	^{238}U	^{235}U	^{234}U	^{236}U
FY92												
Pantex	0.0020			Depleted U	0.9975	0.0025	5×10^{-6}			3×10^{-5}	0.00019	
GA		0.14		93% Enriched U	0.0550	0.9315	0.0098	0.0040	0.0012		4.1	0.017
FERMCO	0.63	0.028	0.60	Not Revised								
USAA	22			Depleted U	0.9975	0.0025	5×10^{-6}			0.35	2.0	
FY93												
ITRI	2.38×10^{-5}	1.01×10^{-7}		Not Revised								
Pantex	0.00816			Depleted U	0.9975	0.0025	5×10^{-6}			0.00013	0.00076	
SNL	0.943			Depleted U	0.9975	0.0025	5×10^{-6}			0.015	0.088	
GA		0.271		93% Enriched U	0.0550	0.9315	0.0098	0.0040	0.0025		8.2	0.034
FERMCO	15.8	0.998	20.2	Not Revised								
USAA	20.6			Depleted U	0.9975	0.0025	5×10^{-6}			0.33	1.9	
Total (Ci)	131	2.18	20.8						0.0082	1.7	48	0.11

corrections also introduce a new uranium isotope, ^{236}U, not previously reported. Overall the uranium inventory is depleted in the lighter isotopes as expected for USDOE waste streams.

The final FY89 to FY93 inventory used in the performance assessment is the sum of the undecayed inventory records from the three disposal units, unclassified shallow land burial, classified shallow land burial, and GCD, combined with revisions described above. The inventory as reported in the Area 5 RWMS database and the revisions made are summarized in Table 2.36.

Table 3-36—Unclassified shallow land burial, classified shallow land burial and GCD radi[illegible]

Table 2.36. continued.

Radionuclide	Unclassified Shallow Land Burial Inventory FY89 to FY93	Classified Shallow Land Burial Inventory FY89 to FY93	Unclassified and Classified GCD Inventory FY89 to FY93	Revisions to Recorded Inventory	Revised Inventory (Undecayed Ci)	Mean Annual Input Rate ($Ci\ yr^{-1}$)

3.0 ANALYSIS OF PERFORMANCE

This chapter describes the development of site-specific scenarios, conceptual models, assumptions, and computer models used in the performance assessment. The first step in the performance assessment process is the development of scenarios. A scenario is defined as the set of features, events, and processes that define the future performance of the burial site. The next step in the performance assessment process is the forming of a detailed schematic model describing the release, transport, and uptake of radionuclides. The development of the schematic model requires that assumptions be made about the magnitude, timing, consequence of the features, events, and processes listed in the scenario. The detailed schematic model is called the conceptual model. Finally, mathematical models are prepared to simulate the conceptual model. This section describes this developmental sequence and the implementation of the final mathematical models.

3.1 SCENARIO DEVELOPMENT AND SELECTION

Uncertainty in performance assessment can be divided into three categories (Bonano and Baca, 1994): uncertainty in the future state of the repository (scenario uncertainty), uncertainty in conceptual models, and uncertainty in parameters. Development and analysis of multiple scenarios is one method to account for scenario uncertainty. The approach of this assessment is to analyze a small number of deterministic scenarios considered to have a reasonable probability of occurrence. This section describes the methodology and rationale of scenario development and selection.

For convenience, two types of scenarios have been developed, the release scenario and the pathway scenario. The release scenario describes the features, events, and processes that might transport radionuclides to the accessible environment. The pathway scenario represents a reasonable, but conservative, view of the pathways in the accessible environment that might transport radionuclides to human receptors. Combined, the two scenarios include all of the features, events, and processes responsible for the transport of radionuclides from the source term to humans.

Intruder scenarios were considered as a special case. Inclusion of a separate intruder performance objective in USDOE Order 5820.2A was assumed to indicate that intruder analyses were required regardless of the probability of occurrence. Intruder scenarios were not viewed as attempts to realistically predict the future, but rather as hypothetical events that are unlikely to ever occur. The intruder scenarios were analyzed to set conservative concentration limits for waste disposed of in the near surface. Developing realistic site-specific intruder scenarios is impossible because predicting human behavior in the future is impossible. The intruder scenarios were assumed to be a construct used to set waste concentration limits. Therefore, rather than develop new site-specific intruder scenarios, this analysis has adopted established scenarios. These scenarios were originally presented by USNRC (1981) and further developed by Kennedy and Peloquin (1988). These scenarios have been used in most LLW performance assessments prepared in the United States. They are reasonable in the sense that they are possible for Frenchman Flat and conservative because they represent a very restrictive future use of the site. The scenarios have been made site-specific by adjusting parameters or eliminating features as appropriate for a Mohave Desert site.

3.1.1 Release Scenarios

The release scenario is a preliminary list of features, events, and processes that describe the release of radionuclides from the source term and surrounding geosphere to the accessible environment. The scenarios were assembled from a screened list of features, events, and processes. This initial screening, based on probability of occurrence, consequence, applicability to the site, and the performance objectives, identified seven broad mechanisms for the release of radionuclides from the disposal site.

In Table 3.1, potential processes releasing radionuclides from a buried LLW source to secondary sources are identified, where secondary sources are defined to be the compartments within the physical environment that may serve as reservoirs of radionuclides for subsequent transport to humans offsite. The potential secondary sources identified include shallow soils (including soil detritus), air, vegetation, surface water, and groundwater in the immediate vicinity of the LLW facility.

Table 3.1. Features, events, and processes considered in the development of the release scenario.

Features, Events, and Processes	Secondary Compartment in Accessible Environment
Diffusion of Gases	Atmosphere, Soil
Diffusion of Dissolved Solutes	Soil

Table 3.1. - continued.
	Secondary Compartment

response to greater moisture available at the exposed trench wall. Evidence from other sites suggests that some introduced species, such as *Salsola*, may have rooting depths as great as 4 m. Limited data on rooting depth of shrubs from Great Basin Desert communities suggest comparable depths. Since a significant fraction of plant biomass becomes soil detritus each year (Section 2.7.1), root uptake of radionuclides from the waste is likely to lead to contamination of shallow soils in addition to contamination of standing plant material. Root production may also contribute to soil contamination. Therefore, plant uptake and transport processes were retained in the final release scenario.

The burrowing activities of animals characterize another form of biointrusion that might result in the release of radionuclides to the soil and vegetation above the disposal units. Burrowing animals found at the NTS include ants, termites, desert tortoises, a number of rodents, burrowing owls, Nuttal's cottontail, kit foxes, and badgers. Invertebrates and rodents are by far the most numerous and significant. Transport of waste and soil to the surface by burrowing animals was retained for the release scenario.

Once contaminated, the shallow soil compartment serves as a source of contamination of air and vegetation above the facility. Wind suspends contaminated soil in the air, which is subsequently deposited back onto the soil and plant surfaces. This process was retained for release scenario development.

The remaining two processes, diffusion and advection of solutes in soil pore water, are dependent on the conceptual model of site hydrology. A preliminary screening was conducted to evaluate the potential of these two processes to transport radionuclides to the surface soil compartment and the uppermost aquifer. These screening analyses appear in the following section.

3.1.1.1 Analysis of Hydrologic Processes Potentially Affecting Release of Radionuclides

A conceptual model of site hydrology based on site characterization data was introduced in Section 2.4.2.2.1. This model proposes that movement of moisture in the vadose zone beneath the Area 5 RWMS is vertical and that three regions of liquid movement can be delineated (Figure 2.22). The matric potential profile data indicate that a conceptual boundary, termed the "zero-flux plane," occurs about 35 m below the ground surface. Above the zero-flux plane (Zone I), moisture will have the tendency to move upward towards the surface due to the increasingly negative matric potential. The large negative matric potential is maintained by the high evaporative demand at the surface. Infiltrating water is believed to be evaporated or transpired back to the atmosphere before passing through

Zone I. Consequently, the current conceptual model assumes that recharge of the aquifer through the alluvial sediments is not occurring at the Area 5 RWMS. All disposal units at the Area 5 RWMS are within Zone I. Two zones exist below the zero-flux plane, Zones II and III. The tendency for water flow below the zero-flux plane is downward to the water table. In summary, the three regions are:

- Zone I: An upper zone of approximately 35 m, where high evapotranspiration at the surface creates a potential for upward flow and drying at the near-surface.

- Zone II: An intermediate zone from about 35 m below the surface down to 150 to 220 m, dominated by gravity drainage or vertical downward flow.

- Zone III: A lower zone immediately above the water table, where the hydraulic potential is near zero and the water is under a capillary fringe condition, with relatively static conditions producing little flow.

The conceptual model described above suggests several radionuclide transport mechanisms. First, the potential for upward flow in Zone I suggests that upward advection of water may occur. In addition to this upward hydrologic transport mechanism, dissolved solutes in the liquid phase may diffuse upward because of the concentration gradient that exits between the waste and the surface soils. Downward transport would be possible for contaminants reaching the zero-flux plane and passing into Zone II. However, since the waste is placed above the zero-flux plane and the travel time from the zero-flux plane to the uppermost upward flow of water and contaminants. Each of the transport processes described above have been evaluated and described in detail in Appendix D. The following sections summarize these results.

3.1.1.1.1 Upward Advection Under Ambient Conditions

The potential for upward advection was assessed by estimating the mean travel time for moisture advected upward from the buried waste to the surface. These analyses assumed geometric mean values for hydraulic parameters and a static matric potential profile as observed for the Science Trench and Borehole study (REECo, 1993c). The estimated time for liquid water to travel up from the top of the emplaced waste to the land surface (2.4 m) (based on matric potential as the only driving force) was about 5×10^8 years. Within 10,000 years, the distance traveled by liquid water is estimated to be less than 0.01 m. The near surface alluvium is normally so dry that a continuous phase of liquid between grain boundaries is unlikely to exist. Consequently, the unsaturated hydraulic conductivity is extremely small and predicted travel times are extremely long. Based on these results, transport by the upward advection of liquid water driven by the water potential gradient was eliminated as a potential transport mechanism.

3.1.1.1.2 Upward Advection Under Wetter Conditions Resulting From Infrequent Rainfall

Downward infiltration of water from the soil surface may occur during and after infrequent precipitation events. The depth of infiltration depends upon the hydrologic characteristics of the alluvium, as well as the duration and intensity of precipitation events. The long-term downward extent of the wetting front depends on the atmospheric conditions which produce evaporation at the soil surface. Wetting of the alluvium to the depth of the waste could allow upward advection to the surface when drying conditions return.

Water content profiles following precipitation events were simulated using a numerical unsaturated flow code (UNSAT2), daily precipitation data for Frenchman Flat, a seasonal evapotranspiration is responsible for reducing the water content in the near surface and is the major factor responsible for preventing water from moving deeper into the profile.

Preliminary data show that the precipitation to evapotranspiration (P/ET) ratio is about 0.07, indicating that rainfall is recycled back into the atmosphere either before it has had the time to infiltrate into the ground surface or soon afterwards. Similar conclusions have been reached at other desert sites in the western United States (Gee et al., 1994; Fouty, 1989; Fischer, 1992; Scanlon, 1994; Scanlon and Milly, 1994; and Scanlon et al., 1991).

The modeling results suggest that infiltrating water is unlikely to reach the depth of the buried waste. Therefore, upward advection under wetter conditions expected after infrequent rainfall was not retained in the final conceptual model.

3.1.1.1.3 Upward Diffusion of Dissolved Solutes

Since advective transport in near surface soils at the Area 5 RWMS is believed to be negligible, it may be appropriate to consider the upward diffusion of dissolved solutes. The diffusion of solutes in soil systems has been recognized for many years to be dependant upon the moisture content of the soil as well as the concentration gradient (Heslep and Black, 1954; Stewart and Eck, 1958; Kemper and van Schaik, 1966). These authors' work suggests that the diffusive flux should be negligible in the extremely dry soils observed at the RWMS where volumetric water content is approximately 0.07.

The upward diffusion of dissolved solutes in the alluvial pore spaces requires a continuous phase of liquid water. The near surface alluvium is believed to be too dry for such a continuous liquid phase to exist. This conclusion is supported by literature reports of Cl^- diffusion in Ca^{2+} saturated systems (Porter et al., 1960), where zero transmission was observed at water contents ranging from 0.077 to 0.155 in a loam soil. Even using the average background water content of alluvium at the RWMS at depth (approximately 0.10 to 0.12), diffusive transport of radionuclides is not expected to be significant.

3.1.1.2 Summary of Hydrologic Processes and Their Effects on Release and Transport of Radionuclides

Based on the hydrologic conceptual model developed from site characterization studies, three

Zone II is not consistent with the conceptual model and was eliminated as a credible transport process during development of the conceptual model. None of the processes evaluated were found to be credible release and transport mechanisms when considered individually. Evaluating these processes simultaneously with other transport processes such as plant uptake is not likely to alter this conclusion. Individually, these hydrologic processes are not expected to transport contamination more than a few centimeters in 10,000 years. Estimates of release by plant uptake or by burrowing animals will not be significantly increased by hydrologic transport on these scales.

The usual condition of the upper 35 m of the alluvium is such that there is a tendency or potential for water to flow upward. The hydraulic conductivity in the upper 2.4 m of the alluvium is extremely low because of the low water content. Although there is a potential for water to move upward, moisture movement is expected to be negligible under the dry conditions that prevail most of the time.

Modeling of infrequent rainfall suggests that infiltrating water does not penetrate deep enough to alter this conclusion. The annual evapotranspiration at the Area 5 RWMS is much larger than the mean annual precipitation. Modeling results suggest that infiltrating water is unlikely to penetrate beyond 0.20 to 0.25 m. This conclusion is supported by results obtained for other analogous desert sites in the western United States.

The low water content of the alluvium is believed to eliminate upward diffusion as a significant release mechanism. Solute diffusion requires a continuous phase of liquid water. Since the average background water content of the near surface alluvium at the RWMS is near the residual water content of from 0.07 to 0.08, it is not reasonable to expect solute diffusion to be significant.

Downward advection in Zone II was eliminated as a transport mechanism during development of the conceptual model because the waste is not placed in Zone II, and the travel time through Zone II to the aquifer is much greater than 10,000 years. The infiltration modeling studies further support this conclusion since they suggest that infiltrating water is extremely unlikely to ever reach the zero-flux plane.

3.1.1.3 Summary of the Final Release Scenario

In Section 3.1.1, seven features, events, and processes leading to release of radionuclides to the accessible environment were introduced. Preliminary screening of the consequences of two of the hydrology dependent processes, advection and diffusion of dissolved solutes, indicate that they are likely of no consequence under prevailing climatic conditions. Review of the remaining five processes (gaseous diffusion, gaseous advection, plant uptake, bioturbation, and resuspension) indicates that none are mutually exclusive. Therefore, they can be combined into a single release scenario.

3.1.2 Pathway Scenarios

In Section 3.1.1, the release scenario for the RWMS facility was described. The analysis of potentially important modes of release of radionuclides to the Area 5 accessible environment suggests that three environmental media may be contaminated: (1) air above the facility, (2) surface soil above the facility, and (3) vegetation above the facility. The pathway scenarios described in this section are lists of the transport pathways leading to exposure of the public. The pathways operating at the site after loss of institutional control will be dependent on land use. No adequate methods exist for predicting the future use of the site or the probability of different uses. Therefore, land use was based on the current pattern of use in southern Nevada. Excluding land uses that result in direct intrusion into buried waste, three general classes of land use were hypothesized: (1) transient occupation of the site for recreational or commercial purposes, (2) open rangeland, and (3) permanent domestic residence with ranching.

The transient occupation scenario accounts for most of the land in southern Nevada. This scenario hypothesizes that members of the public visit the site but will not reside at the site or engage in any agricultural activities. Members of the public were not assumed to be engaged in any specific activity since all of the potential uses involve the same exposure pathways. The likely pathways of exposure are inhalation of suspended soil and external irradiation. This scenario is assumed to begin at the end of institutional control.

The open rangeland scenario assumes that a remotely located ranch uses the site to graze residents are exposed through the atmospheric pathway only. After institutional control, residents may consume contaminated meat and dairy products from range fed cattle grazing over the site.

The final potential scenario hypothesizes that a deep groundwater well has been developed near the site and ample water is available. Establishment of a permanent residence on or near the site is feasible with the added availability of water. It is also reasonable to assume that the residents might engage in agricultural activities. Based on current agricultural land use, a resident could reasonably be expected to engage in commercial ranching activities, including cultivation of irrigated forage crops and non-commercial production of fruits, vegetables, and dairy products. This scenario includes all the pathways described for a transient occupant and an offsite ranch, plus ingestion of contaminated vegetables and soil. Groundwater pathways, however, are not considered credible.

The first two scenarios, transient occupation and open rangeland, are considered the most probable, as they do not require development of water resources at the site. These are the activities currently observed for areas where water resources are lacking such as Frenchman Flat. In southern Nevada, urban development or cultivation of irrigated crops is tied to the availability of surface water or shallow groundwater. Such resources are not available at the Area 5 RWMS. There are few economic incentives to develop this land because of the limited agricultural potential and great expense of obtaining deep groundwater. Although the resident farming scenario is technically feasible, it is considered highly improbable based on current land use patterns. Therefore, this scenario was eliminated because of its low probability of occurrence.

Two pathway scenarios were developed based on the remaining land use options, transient occupation and open rangeland. Table 3.2 lists the pathways transferring contamination to members of the general public for each scenario adopted. Note that the open rangeland scenario has both an institutional control period and a post-institutional control period where different pathways operate. The two pathways scenarios are not mutually exclusive. Conceptual models developed and assumptions made to quantify these exposures are discussed in Section 3.4.

Table 3.2. Pathways included in the transient occupation and open rangeland scenarios.

In the intruder-construction scenario, an individual is exposed to waste while constructing a residence on the site. It is assumed that the intruder does not recognize the hazardous nature of the material excavated. The discovery scenario is similar to the intruder-construction scenario, except that the intruder is assumed to recognize the hazardous nature of the waste. Once this occurs, the intruder leaves the site and the exposure ceases. The discovery scenario was developed to account for early intrusion, when the waste has not decomposed. This assessment takes no credit for waste form stability and it is, therefore, assumed that the discovery and intruder-construction scenario can occur at the same time. Under this assumption, the only difference between the discovery and the intruder-construction scenarios is the duration of exposure. Since the exposure in the intruder-construction scenario bounds that of the acute discovery scenario, the latter scenario can be eliminated.

The intruder-construction scenario assumes that an intruder constructs a domestic residence on the site over a period of 500 hours. The intruder is exposed to radioactive constituents in the waste during the excavation of a basement. The intruder is exposed to the exhumed waste by:

- inhalation of resuspended contaminated soil, and
- external irradiation by contaminated soil.

The drilling scenario assumes the short-term exposure of a hypothetical intruder to drill cuttings from a borehole penetrating the waste disposal site. This scenario provides an intruder exposure scenario for wastes buried below the depth of typical construction excavations. The drilling intruder is assumed to be exposed for approximately 100 hours to contaminated drill cuttings while drilling a drinking water well into the uppermost aquifer.

The drilling method is assumed to be a wet drilling technique that will generate minimal dust loading. The intruder is exposed to the exhumed waste by:

- inhalation of resuspended contaminated drill cuttings, and
- external irradiation by contaminated drill cuttings.

Previously described chronic intruder scenarios include the intruder-agriculture, intruder-resident, and post-drilling scenario. The intruder-agriculture scenario follows the intruder-construction scenario. Under this scenario, it is assumed that the intruder resides at the site after constructing a residence and engages in agricultural activities on the contaminated site. The intruder-agriculture scenario involves exposure to a soil-waste mixture of the same concentration as the acute intruder-construction scenario. However, since the intruder-agriculture scenario involves a longer exposure time, the chronic intruder-agriculture scenario bounds the acute intruder-construction scenario and the latter can be eliminated from consideration.

The USNRC intruder-agriculture scenario (USNRC, 1981), hypothesized exposure to waste from some type of excavation made during the construction of a building at the site. Traditionally, this excavation has been assumed to be a basement. In southern Nevada, residences are very rarely constructed with a basement. This is believed to be due to economic factors. However, excavations can still be prepared during the construction of a slab on grade structure. Current construction practices can involve grading or terracing of the site, trenching for utilities, and excavations for septic tanks or other underground storage tanks. Furthermore, soil structure at the Area 5 RWMS does not physically preclude excavation. The intruder-agriculture scenario with basement construction was retained because it is physically possible for this site.

Under the intruder-agriculture scenario, it is assumed that an intruder constructs a residence with a basement on the site and, in the process, exhumes buried waste. The soil and waste from the excavation is spread over an area surrounding the house and mixed homogeneously. The resident is assumed to raise livestock, fruits, and vegetables in the contaminated area. Although the intruder uses groundwater from below the site, there are no groundwater dependent pathways because contamination of the aquifer is considered physically unreasonable. The intruder is exposed to contamination by:

- inhalation of resuspended contaminated soil,
- inhalation of gaseous radionuclides released from the site,
- external irradiation by contaminated soil,
- ingestion of contaminated soil,
- ingestion of contaminated beef and milk, and
- ingestion of contaminated fruits and vegetables.

Under the intruder-resident scenario, it is assumed that the intruder lives directly on the waste form after it is exposed, either by an excavation or some natural process. The extremely unlikely for this site. Waste forms at the Area 5 RWMS are predominately steel drums, steel boxes, and wooden boxes. It is not credible that these waste forms will provide

The post-drilling scenario is an extension of the drilling scenario. It assumes that the intruder occupies the site after drilling a water well and grows crops on a mixture of clean soil and contaminated drill cuttings. After exhumation of waste, the exposure pathways are the same as for the intruder-agriculture scenario. The only differences between the two radionuclides from the shallow land burial source term. No case is required for release of volatile radionuclides from the special case thorium waste since it does not include ^{3}H, ^{14}C, or ^{85}Kr source terms.

Five modeling cases have been identified for intruder analysis (Table 3.4). The special case thorium waste can be exempted from the intruder-agriculture scenario since no credible construction excavation can occur to the depth of thorium burial which is 12.2 m.

3.2 CONCEPTUAL MODELS AND ASSUMPTIONS

This section describes the conceptual models and assumptions used in the performance assessment. The conceptual model is a detailed and quantitative description of the processes assumed to be affecting site performance. It is developed by making assumptions about the timing, magnitude and consequence of the events, and features and processes included in the scenario. In the final step, mathematical expressions are formulated that simulate the performance of the conceptual model.

3.2.1 Source Term

The source term is the contents of the waste disposal cells including the radionuclides available for release to the surrounding environment. Source term conceptual models have been developed that describe the geometry of a shallow land burial pit, the special case thorium waste cell (Pit 6), and the temporary closure cap. Additional conceptual models describe the performance of the waste containers and waste forms.

3.2.1.1 Estimated Inventory at Site Closure

An estimate of the site inventory at closure has been prepared to estimate long-term site performance. This section describes the projected inventory for shallow land burial and for the special case thorium waste cell.

The inventory at closure was estimated by assuming that waste received in the future would have the same activity concentration as wastes received from FY89 through FY93. As the mission of USDOE shifts from production to decommissioning and environmental restoration, confidence in this estimate may be reduced. Experience has shown that most of the techniques available to forecast future waste receipts are very unreliable. The analysis presented here, an analysis of an inventory estimated from past waste disposal, has been performed to provide reasonable assurance that waste streams accepted since the

Table 3.3. Summary of all pathways modeling cases selected for analysis.

Cases for Analysis	Release Scenario	Pathway Scenarios	
	Base Case	Transient Occupation	Open Rangeland
Non-Volatile Nuclides - Shallow Land Burial	X	X	X
Non-Volatile Nuclides - Special Case Thorium Waste (Pit 6)			
Radon-Shallow Land Burial	X		
Radon-Special Case Thorium Waste (Pit 6)	X		
Other Volatiles (^{3}H, ^{14}C, ^{85}Kr) - Shallow Land Burial	X	X	X

Table 3.4. Summary of intruder modeling cases selected for analysis.

Cases for Analysis	Acute Intruder Scenarios	Chronic Intruder Scenarios	
	Drilling	Intruder-Agriculture	Post Drilling
Shallow Land Burial	X	X	X
Special Case Thorium Waste (Pit 6)	X		X

implementation of USDOE Order 5820.2A meet the performance objectives. Assurance of compliance with the performance objectives in the future will be obtained through the development and use of waste acceptance criteria based on site-specific performance assessment results.

The shallow land burial source term assumes a constant rate of disposal from FY89 to FY2028 and includes the effects of radioactive decay and ingrowth. The assumed annual disposal rate was the mean activity disposal rate from FY89 through FY93 (Tables 2.36).

The rate of change of the activity of each radionuclide up until closure is given by:

$$\begin{aligned} \frac{dq_1}{dt} &= R_1 - \lambda_1 q_1, \\ \frac{dq_2}{dt} &= R_2 + f_1 \lambda_2 q_1 - \lambda_2 q_2, \\ \frac{dq_3}{dt} &= R_3 + f_2 \lambda_3 q_2 - \lambda_3 q_3, \\ &\vdots \\ \frac{dq_n}{dt} &= R_n + f_{n-1} \lambda_n q_{n-1} - \lambda_n q_n, \end{aligned} \tag{3.1}$$

where:

q_i	=	activity of the ith member of the chain , Ci,
R_i	=	mean annual disposal rate of ith member of the chain, (from Table 2.36), Ci yr^{-1},
λ_i	=	radioactive decay constant of the ith member of the chain, yr^{-1}, and
f_i	=	branching fraction from (i - 1) member of the chain to ith member.

For radionuclides without a supporting parent (i.e. the case where i = 1), the analytical solution,

$$q_1 = \frac{R_1}{\lambda_1} (1 - e^{-\lambda_1 t}) \tag{3.2}$$

was used to calculate the activity present at closure or the end of FY2028. Several approaches were used for members of radioactive decay chains. Eight long, serial-decay chains and five short, two-member chains were identified from inventory records (Table 3.5). The two-member chains considered were ^{90}Sr-^{90}Y, ^{93}Zr-^{93}Nb, ^{126}Sn-^{126}Sb, ^{137}Cs-^{137m}Ba, and ^{152}Eu-^{152}Gd.

All of the two-member chains were assumed to be in secular equilibrium at 2028, except the ^{152}Eu-^{152}Gd pair. The ^{152}Gd half-life, 1.1×10^{14} years, is considerably longer than the [illegible]

Table 3.5. Serial radioactive decay chains present in the Area 5 inventory. Radionuclides determined by BAT6CHN are indicated in italics. All other radionuclides are assumed to be in secular or transient equilibrium with the parent in italics by the end of the institutional control period.

Chain 1	Chain 2	Chain 3	Chain 4	Chain 5	Chain 6	Chain 7	Chain 8
$^{243}\mathit{Am}$	$^{241}\mathit{Pu}$	$^{242}\mathit{Pu}$	$^{238}\mathit{Pu}$	$^{244}\mathit{Cm}$	$^{248}\mathit{Cm}$	$^{243}\mathit{Cm}$	$^{232}\mathit{U}$
$^{239}\mathrm{Np}$	$^{241}\mathit{Am}$	$^{238}\mathit{U}$	$^{234}\mathit{U}$	$^{240}\mathit{Pu}$	$^{244}\mathit{Pu}$	$^{239}\mathit{Pu}$	$^{228}\mathit{Th}$
$^{239}\mathit{Pu}$	$^{237}\mathit{Np}$	$^{234}\mathrm{Th}$	$^{230}\mathit{Th}$	$^{236}\mathit{U}$	$^{240}\mathrm{U}$	$^{235}\mathit{U}$	$^{224}\mathrm{Ra}$
$^{235}\mathit{U}$	$^{233}\mathrm{Pa}$	$^{234m}\mathrm{Pa}$	$^{226}\mathit{Ra}$	$^{232}\mathit{Th}$	$^{240m}\mathrm{Np}$	$^{231}\mathrm{Th}$	$^{220}\mathrm{Rn}$
$^{231}\mathrm{Th}$	$^{233}\mathit{U}$	$^{234}\mathrm{Pa}$	$^{222}\mathrm{Rn}$	$^{228}\mathit{Ra}$	$^{240}\mathrm{Np}$	$^{231}\mathit{Pa}$	$^{216}\mathrm{Po}$
$^{231}\mathit{Pa}$	$^{229}\mathit{Th}$	$^{234}\mathit{U}$	$^{218}\mathrm{Po}$	$^{228}\mathrm{Ac}$	$^{240}\mathit{Pu}$	$^{227}\mathit{Ac}$	$^{212}\mathrm{Pb}$
$^{227}\mathit{Ac}$	$^{225}\mathrm{Ra}$	$^{230}\mathit{Th}$	$^{214}\mathrm{Pb}$	$^{228}\mathit{Th}$	$^{236}\mathit{U}$	$^{223}\mathrm{Fr}$	$^{212}\mathrm{Bi}$
$^{223}\mathrm{Fr}$	$^{225}\mathrm{Ac}$	$^{226}\mathit{Ra}$	$^{214}\mathrm{Bi}$	$^{224}\mathrm{Ra}$	$^{232}\mathit{Th}$	$^{227}\mathrm{Th}$	$^{212}\mathrm{Po}$
$^{227}\mathrm{Th}$	$^{221}\mathrm{Fr}$	$^{222}\mathrm{Rn}$	$^{214}\mathrm{Po}$	$^{220}\mathrm{Rn}$	$^{228}\mathit{Ra}$	$^{223}\mathrm{Ra}$	$^{208}\mathrm{Tl}$
$^{223}\mathrm{Ra}$	$^{217}\mathrm{At}$	$^{218}\mathrm{Po}$	$^{210}\mathit{Pb}$	$^{216}\mathrm{Po}$	$^{228}\mathrm{Ac}$	$^{219}\mathrm{Rn}$	
$^{219}\mathrm{Rn}$	$^{213}\mathrm{Bi}$	$^{214}\mathrm{Pb}$	$^{210}\mathrm{Bi}$	$^{212}\mathrm{Pb}$	$^{228}\mathit{Th}$	$^{215}\mathrm{Po}$	
$^{215}\mathrm{Po}$	$^{209}\mathrm{Tl}$	$^{214}\mathrm{Bi}$	$^{210}\mathrm{Po}$	$^{212}\mathrm{Bi}$	$^{224}\mathrm{Ra}$	$^{211}\mathrm{Pb}$	
$^{211}\mathrm{Pb}$	$^{213}\mathrm{Po}$	$^{214}\mathrm{Po}$		$^{212}\mathrm{Po}$	$^{220}\mathrm{Rn}$	$^{211}\mathrm{Bi}$	
$^{211}\mathrm{Bi}$	$^{209}\mathrm{Pb}$	$^{210}\mathit{Pb}$		$^{208}\mathrm{Tl}$	$^{216}\mathrm{Po}$	$^{207}\mathrm{Tl}$	
$^{207}\mathrm{Tl}$		$^{210}\mathrm{Bi}$			$^{212}\mathrm{Pb}$	$^{211}\mathrm{Po}$	
$^{211}\mathrm{Po}$		$^{210}\mathrm{Po}$			$^{212}\mathrm{Bi}$		
					$^{212}\mathrm{Po}$		
					$^{208}\mathrm{Tl}$		

Table 3.6. Radionuclide half-lives, branching fractions, and equilibrium factors used in the performance assesment (from Negin and Worku, 1990).

Radionuclide	Half-life (yr)	Branching Fraction	Equilibrium Factor
^{3}H	12.8	---	---
^{14}C	5730	---	---
^{36}Cl	3.01×10^{5}	---	---
^{59}Ni	75000	---	---
^{60}Co	5.27	---	---
^{63}Ni	100	---	---
^{79}Se	65000	---	---
^{85}Kr	10.7	---	---
^{90}Sr ^{90}Y	28.6 0.00732	--- 1.0	--- 1.0
^{93}Zr ^{93}Nb	1.53×10^{6} 14.6	--- 1.0	--- 1.0
^{99}Tc	2.13×10^{5}	---	---
^{107}Pd	6.5×10^{6}	---	---
^{126}Sn ^{126}Sb	1×10^{5} 0.034	--- 1.0	--- 1.0
^{129}I	1.57×10^{7}	---	---
^{133}Ba	10.5	---	---
^{135}Cs	2.3×10^{6}	---	---
^{137}Cs ^{137m}Ba	30.17 4.85×10^{-6}	--- 0.946	--- 1.0
^{151}Sm	90	---	---
^{152}Eu ^{152}Gd	13.6 1.1×10^{14}	--- 0.278	--- No equilibrium
^{154}Eu	8.8	---	---
^{207}Bi	33.4	---	---

Table 3.6 - continued.			
Radionuclide	**Half-life (yr)**	**Branching Fraction**	**Equilibrium Factor**
^{232}U	72	---	---
^{228}Th	1.913	1.0	1.0
^{243}Am	7.38×10^{3}	---	---
^{239}Np	6.45×10^{-3}	1.0	1.0
^{239}Pu	2.41×10^{4}	---	---
^{235}U	7.04×10^{8}	---	---
^{231}Th	2.91×10^{-3}	1.0	1.0
^{231}Pa	3.28×10^{4}	---	---
^{227}Ac	21.2	---	1.0
^{223}Fr	4.15×10^{-5}	0.0138	1.0
^{227}Th	5.13×10^{-2}	0.9862	1.0
^{223}Ra	3.93×10^{-2}	1.0	1.0
^{219}Rn	1.26×10^{-7}	1.0	1.0
^{215}Po	2.48×10^{-11}	1.0	1.0
^{211}Pb	6.87×10^{-5}	1.0	1.0
^{211}Bi	4.05×10^{-6}	1.0	1.0
^{207}Tl	9.07×10^{-6}	0.9973	1.0
^{211}Po	1.64×10^{-8}	0.0027	1.0
^{241}Pu	14.4	---	---
^{241}Am	432	---	---
^{237}Np	2.14×10^{6}	---	---
^{233}Pa	7.39×10^{-2}	1.0	1.0
^{233}U	1.59×10^{5}	---	---
^{229}Th	7.34×10^{3}	---	---
^{225}Ra	4.05×10^{-2}	1.0	1.0
^{225}Ac	2.74×10^{-2}	1.0	1.0
^{221}Fr	9.13×10^{-6}	1.0	1.0
^{217}At	1.02×10^{-9}	1.0	1.0
^{213}Bi	8.68×10^{-5}	1.0	1.0
^{209}Tl	4.19×10^{-6}	0.0216	1.0
^{213}Po	1.33×10^{-13}	0.9784	1.0
^{209}Pb	3.71×10^{-4}	1.0	1.0

Table 3.6 - continued.			
Radionuclide	**Half-life (yr)**	**Branching Fraction**	**Equilibrium Factor**
^{242}*Pu*	3.76×10^{5}	---	---
^{238}*U*	4.47×10^{9}	---	---
^{234}Th	6.60×10^{-2}	1.0	1.0
^{234m}Pa	2.23×10^{-6}	1.0	1.0
^{234}Pa	7.65×10^{-4}	0.0016	1.0
^{238}*Pu*	87.8	---	---
^{234}*U*	2.44×10^{5}	---	---
^{230}*Th*	7.7×10^{4}	---	---
^{226}*Ra*	1600	---	---
^{222}Rn	1.05×10^{-2}	1.0	1.0
^{218}Po	5.80×10^{-6}	1.0	1.0
^{214}Pb	5.10×10^{-5}	1.0	1.0
^{214}Bi	3.79×10^{-5}	1.0	1.0
^{214}Po	2.02×10^{-12}	1.0	1.0
^{210}*Pb*	22.3	---	---
^{210}Bi	6.1×10^{-3}	1.0	1.0
^{210}Po	0.379	1.0	1.018
^{244}*Cm*	18.1	---	---
^{248}*Cm*	3.39×10^{5}	---	---
^{244}*Pu*	8.26×10^{7}	---	---
^{240}U	1.60×10^{-3}	1.0	1.0
^{240m}Np	1.41×10^{-5}	1.0	1.0
^{240}Np	1.23×10^{-4}	0.0011	1.0
^{240}*Pu*	6540	---	---
^{236}*U*	3.42×10^{6}	---	---
^{232}*Th*	1.40×10^{10}	---	---
^{228}*Ra*	5.75	---	---
^{228}Ac	7.00×10^{-4}	1.0	1.0

Table 3.6 - continued.			
Radionuclide	**Half-life (yr)**	**Branching Fraction**	**Equilibrium Factor**
^{228}Th	1.91	---	---
^{224}Ra	9.92×10^{-3}	1.0	1.0
^{220}Rn	1.76×10^{-6}	1.0	1.0
^{216}Po	4.63×10^{-9}	1.0	1.0
^{212}Pb	1.21×10^{-3}	---	1.0
^{212}Bi	1.15×10^{-4}	---	1.0
^{212}Po	9.45×10^{-15}	0.6407	1.0
^{208}Tl	5.81×10^{-6}	0.3593	1.0

Table 3.7. Estimated activity and activity concentration of wastes projected to be disposed of by shallow land burial at the Area 5 RWMS from FY89 to FY2028.

Radionuclide	Estimated Activity at Closure in 2028 (Ci)	Estimated Mean Activity Concentration at Closure in 2028 (Ci m^{-3})
^{3}H	3.18×10^{5}	0.864
^{14}C	4.12	1.12×10^{-5}
^{36}Cl	1.54×10^{-7}	4.18×10^{-13}
^{59}Ni	2.34×10^{-5}	6.36×10^{-11}
^{60}Co	0.207	5.68×10^{-7}
^{63}Ni	3.73	1.01×10^{-5}
^{85}Kr	0.0265	7.18×10^{-8}
^{90}Sr ^{90}Y	4.89 4.89	1.33×10^{-5} 1.33×10^{-5}
^{93}Zr ^{93}Nb	3.74×10^{-5} 3.74×10^{-5}	1.02×10^{-10} 1.02×10^{-10}
^{99}Tc	4.99×10^{-4}	1.36×10^{-9}
^{107}Pd	1.09×10^{-5}	2.96×10^{-11}
^{126}Sn ^{126}Sb	1.29×10^{-5} 1.29×10^{-5}	3.50×10^{-11} 3.50×10^{-11}
^{129}I	3.28×10^{-6}	8.91×10^{-12}

Table 3.7 - continued.

Radionuclide	Estimated Activity at Closure in 2028 (Ci)	Estimated Mean Activity Concentration at Closure in 2028 (Ci m^{-3})
^{133}Ba	1.47×10^{-4}	2.00×10^{-10}

Table 3.7 - continued.

Radionuclide	Estimated Activity at Closure in 2028 (Ci)	Estimated Mean Activity Concentration at Closure in 2028 (Ci m^{-3})
^{237}Np	7.91×10^{-3}	2.15×10^{-8}
^{233}Pa	7.91×10^{-3}	2.15×10^{-8}
^{233}U	1.28×10^{-3}	3.48×10^{-9}
^{229}Th	2.29×10^{-6}	6.22×10^{-12}
^{225}Ra	2.29×10^{-6}	6.22×10^{-12}
^{225}Ac	2.29×10^{-6}	6.22×10^{-12}
^{221}Fr	2.29×10^{-6}	6.22×10^{-12}
^{217}At	2.29×10^{-6}	6.22×10^{-12}
^{213}Bi	2.29×10^{-6}	6.22×10^{-12}
^{209}Tl	4.95×10^{-8}	1.34×10^{-13}
^{213}Po	2.24×10^{-6}	6.08×10^{-12}
^{209}Pb	2.29×10^{-6}	6.22×10^{-12}
^{242}Pu	2.34×10^{-3}	6.35×10^{-9}
^{238}U	1.02×10^{3}	2.76×10^{-3}
^{234}Th	1.02×10^{3}	2.76×10^{-3}
^{234m}Pa	1.02×10^{3}	2.76×10^{-3}
^{234}Pa	1.63	4.42×10^{-6}
^{238}Pu	127	3.45×10^{-4}
^{234}U	534	1.45×10^{-3}
^{230}Th	0.606	1.65×10^{-6}
^{226}Ra	0.0906	2.46×10^{-7}

Table 3.7 - continued.		
Radionuclide	**Estimated Activity at Closure in 2028 (Ci)**	**Estimated Mean Activity Concentration at Closure in 2028 (Ci m^{-3})**
^{248}Cm	6.74×10^{-10}	1.83×10^{-15}
^{244}Pu	negligible	negligible
^{240}U		
^{240m}Np		
^{240}Np		
^{240}Pu	24.7	6.72×10^{-5}
^{236}U	0.858	2.33×10^{-6}
^{232}Th	1.89	5.13×10^{-6}
^{228}Ra	1.46	3.98×10^{-6}
^{228}Ac	1.46	3.98×10^{-6}
^{228}Th	1.42	3.86×10^{-6}
^{224}Ra	1.42	3.86×10^{-6}
^{220}Rn	1.42	3.86×10^{-6}
^{216}Po	1.42	3.86×10^{-6}
^{212}Pb	1.42	3.86×10^{-6}
^{212}Bi	1.42	3.86×10^{-6}
^{212}Po	0.910	2.47×10^{-6}
^{208}Tl	0.510	1.39×10^{-6}

negligible - less than 1×10^{-12} Ci

are predominately ^{232}Th and its progeny. Small amounts of ^{230}Th present in the original ore were carried through the refining process and are present in the waste. The ^{230}Th will generate ^{222}Rn gas as ^{226}Ra is produced by radioactive decay. The peak ^{226}Ra concentration will occur in 9,000 to 10,000 years.

The FEMP shipped 368 m^3 of thorium waste to the NTS in FY92. An inventory at closure can be estimated assuming that the lower cell of Pit 6 will be filled with waste having the activity of ^{232}Th, ^{228}Th, and ^{230}Th was calculated as the product of the activity concentration of FY92 waste and the volume of the lower cell of Pit 6.

Based on generator-supplied information, the members of the ^{232}Th decay were assumed to be in secular equilibrium at the time of disposal. This suggests that at least 30 years of ingrowth had occurred by 1992. Assuming that the trench is filled and closed by 2028, approximately 66 years of decay and ingrowth will have occurred by closure. The activity at closure was calculated assuming an initially pure source of ^{232}Th, ^{228}Th, and ^{230}Th and 66 years of decay (Table 3.8).

Table 3.8. Preliminary estimate of the inventory of special case thorium waste that could be disposed of in the lower cell of Pit 6 (PO6U).

Radionuclide	Estimated Activity at Closure in 2028 (Ci)	Estimated Mean Activity Concentration at Closure in 2028 (Ci m^{-3})
^{232}Th	277	0.0495
^{228}Ra	277	0.0495
^{228}Ac	277	0.0495
^{228}Th	277	0.0495
^{224}Ra	277	0.0495
^{220}Rn	277	0.0495
^{216}Po	277	0.0495
^{212}Pb	277	0.0495
^{212}Bi	277	0.0495
^{212}Po	177	0.0317
^{208}Tl	99.6	0.0178
^{230}Th	42.9	7.66×10^{-3}
^{226}Ra	1.21	2.16×10^{-4}
^{222}Rn	1.21	2.16×10^{-4}
^{218}Po	1.21	2.16×10^{-4}
^{214}Pb	1.21	2.16×10^{-4}
^{214}Bi	1.21	2.16×10^{-4}
^{214}Po	1.21	2.16×10^{-4}
^{210}Pb	0.694	1.24×10^{-4}
^{210}Bi	0.694	1.24×10^{-4}
^{210}Po	0.689	1.23×10^{-4}

3.2.1.3 Shallow Land Burial Waste Cell Conceptual Model

Low-level radioactive wastes and mixed wastes have been managed at the Area 5 RWMS by burial in shallow unlined pits and trenches and by burial in GCD boreholes. The dimensions of pits and trenches at the RWMS is variable. The dimensions have been selected to fit within the boundaries of the site and existing excavations, so that land allocated to waste disposal is fully utilized. In contrast, GCD dimensions have remained constant. This section describes a conceptual model of a trench used in performance assessment modeling. A single generic waste disposal cell was used in the analyses to avoid performing analyses for each pit and trench. It is not believed that performing separate analyses for each pit and trench, with its unique dimensions, will add any greater confidence to the results of the performance assessment. The dimensions likely to have the greatest impact on model results are the thickness of the cap and the thickness of the waste due to the one dimensional nature of the analyses. The cap thickness is constant for all waste cells and the thickness of the waste is the least variable of the waste cell dimensions (see Table 2.17). Most waste cells have been excavated to approximately 6 m, allowing placement of four tiers of 1.2 m boxes and 1.2 m of cover soil to return to grade.

Several approaches to developing a conceptual model of a waste disposal cell were investigated before it was decided to use the dimensions of Pit 4 (P04U). These approaches included mean excavation dimensions and weighted (with respect to volume and activity) mean excavation dimensions. Both these approaches yielded dimensions that were not

3.2.1.4 Conceptual Model of Cap Performance

The Integrated Closure Program is preparing a closure strategy for the Area 5 RWMS. A final closure plan will not be available for several years. Since there is no closure design available for use in the performance assessment, the conceptual model of the cap system is based on the temporary closure cap installed during the operational period. A final closure cap is certain to consider design criteria that will enhance performance relative to the temporary closure cap. Use of the temporary closure cap in the performance assessment is expected to yield conservative results.

The temporary closure cap consists of 2.4 m of screened alluvium. Approximately half of this thickness, 1.2 m, is below the existing grade and half is above grade (Figure 3.1). The temporary cap is assumed to remain intact throughout the 100-year active institutional control period. After active institutional control, native desert flora and fauna are assumed to repopulate the site. The cap is assumed to be subjected to natural erosional and depositional processes after active institutional control ends.

All available data suggest that net sediment accumulation is occurring on the three coalescing alluvial fans at the RWMS. Long-term net deposition rates have been derived from age-dated horizons near or within the Area 5 RWMS. Net deposition rates have been tentatively reported as 3×10^{-5} m yr^{-1}, 7×10^{-5} m yr^{-1}, and 2×10^{-4} m yr^{-1} (RSN, 1991a). Values at the low end of this range are consistent with reports from other arid regions (RSN, 1991a) and a deposition rate of 3×10^{-5} m yr^{-1} is assumed to be best estimate available for the alluvial fans surrounding the RWMS.

Since the cap is elevated above grade, it is not subject to the same erosional environment as the surrounding alluvial fans. Sediment is deposited on the alluvial fans at the RWMS by erosion from mountain slopes higher in the Halfpint Range and from reworking of alluvial sediments. Sediment is transported in suspension or as a bed load to a lower elevation where the slope and velocity of the runoff is insufficient to maintain sediment transport. Water flowing down gradient from the surrounding ranges will not flow over the intact closure cap because of its elevation above grade. Sediment accumulation is not expected to be significant while the cap remains above grade.

Erosion in ephemeral streams is not expected to have a significant impact on site performance. Water flowing in ephemeral channels may erode sediments from the channel bed. At any given time the land area within active ephemeral channels is small. Over time, the channels can be expected to change course. The depth of these channels is usually less

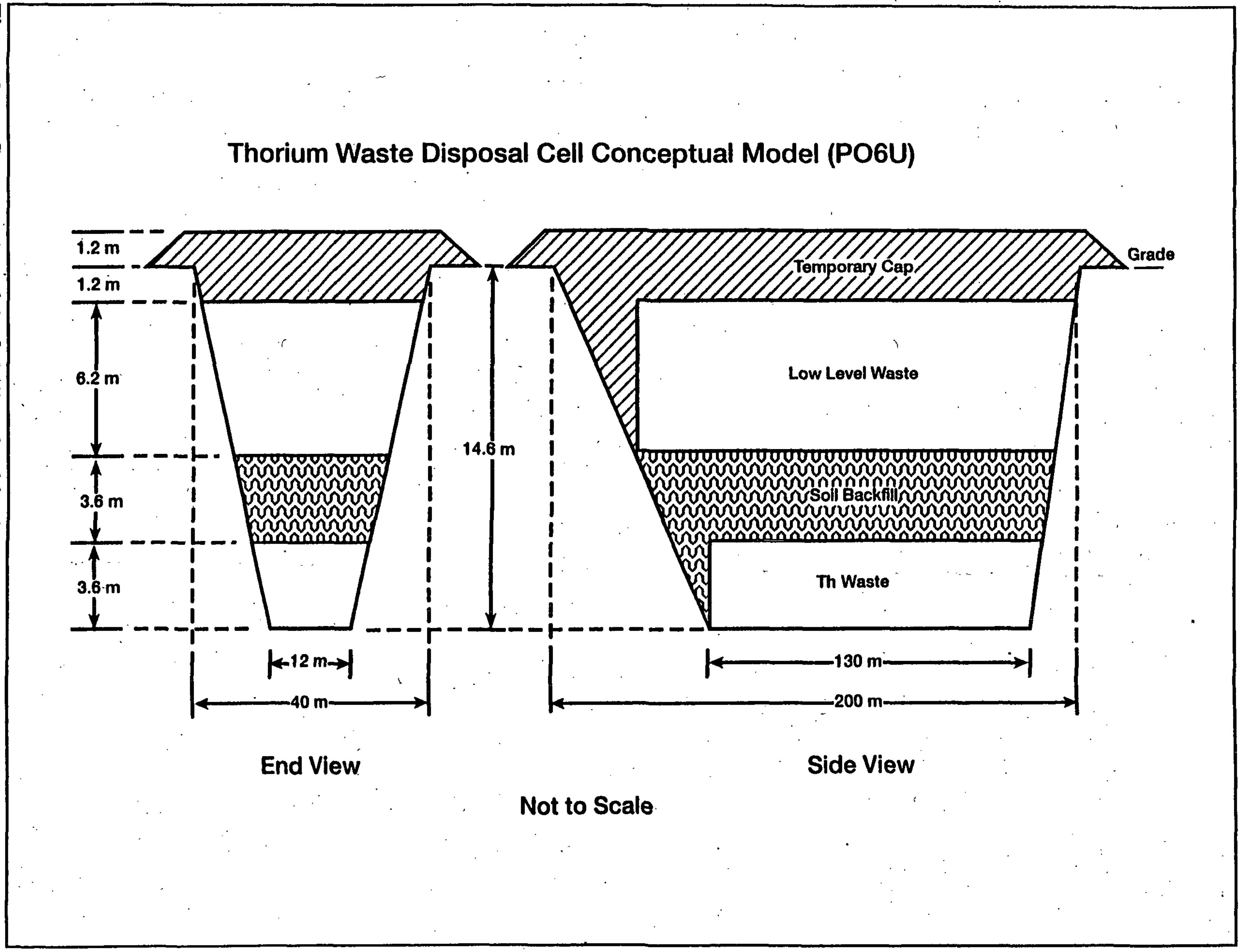


Figure 3.1 - Conceptual model of shallow land burial pits and trenches.

than 0.8 m in the vicinity of the Area 5 RWMS. Channels deeper than 2 m are very unlikely at the site (Section 2.4.1.1). The primary consequence of ephemeral channels is believed to be a mixing or reworking of alluvium within 1 m of the surface. These channels are not deep enough or extensive enough in area to represent an important preferential pathway for release. Furthermore, ephemeral channels are unlikely to be active on the cap while it is still above grade. Therefore, it is hypothesized that the intact cap will not be subject to any significant sediment accumulation and reworking until the surrounding fan rises to the elevation of the cap.

While the cap is above grade it will be subject to erosion from direct precipitation and from wind. Cap erosion by precipitation can be bounded using the Universal Soil Loss Equation (USLE) (Donahue et al., 1983). The USLE was not developed for arid non-agricultural environments, such as the NTS, but can provide conservative estimates of the magnitude of erosion (Yu et al., 1993). The USLE provides erosion estimates of approximately 1×10^{-5} m yr^{-1} (Table 3.9). Erosion at a rate of 1×10^{-5} m yr^{-1} will reduce cap thickness by only 0.1 m in 10,000 years.

Table 3.9. Parameter values assumed for the Universal Soil Loss Equation.

Universal Soil Loss Equation: A = R K LS C P (3.3)	
Parameter	**Assumed Value**
R - Rainfall Erosivity	20
K - Soil Erodibility Index	0.10
LS - Length Slope Factor	0.25
C - Crop Management Factor	0.18
P - Erosion Control Practice Factor	1.0
ρ - Soil Bulk Density	1.65 g cm^{-3}
A = 0.09 ton acre^{-1} yr^{-1} (1×10^{-5} m yr^{-1} for ρ = 1.65 g cm^{-3})	

Wind erosion rates are more difficult to quantitatively estimate. The temporary closure caps are constructed from screened native alluvium that still contains gravels and cobbles too large to be moved by eolian forces. Therefore, it is assumed that after some period of wind erosion, the surface of the cap will become armored with gravel and wind erosion will cease. The native alluvium is approximately 25 percent gravel by mass (Figure 2.11). Therefore, several centimeters of gravel armor should be present after the erosion of as little as 0.1 m of soil.

Conceptually, cap performance can be divided into two periods. There will be an initial period when the cap is above grade. During this period, slow erosion from direct

3.2.1.6 Waste Form Conceptual Model

The chemical and physical form of the waste and the integrity of the containers can have an impact on radionuclide release calculations, especially in an arid environment. Wastes disposed of at the Area 5 RWMS are packaged predominately in metal drums, metal boxes, and wooden boxes. An accurate breakdown of containers by type and construction material cannot be obtained from the database. Little is known concerning the degradation of containers under the conditions prevalent at the NTS. No information concerning the chemical or physical form of the waste can be obtained from the site database.

Based on the lack of information about the waste form and containers, it was necessary to adopt a very conservative model. Waste packages were assumed to completely degrade by the end of institutional control. No credit was taken for the waste forms' ability to resist release and dispersion. The waste was assumed to have degraded to a material indistinguishable from soil by the end of institutional control. Under the arid conditions of the NTS, most wastes are likely to survive intact for a considerable time. However, in the absence of hard data concerning likely survival times, very conservative assumptions were adopted.

3.2.2 Release Scenario Assumptions and Conceptual Models

This section describes the conceptual models and assumptions for the base-case release scenario. The base-case release scenario was described in Section 3.1. The processes assumed for the scenario include diffusion and advection of volatile radionuclides, uptake of radionuclides by native plants, soil excavation by burrowing animals, and resuspension of contaminated soil (Table 3.1).

The release scenario describes the processes transporting volatile and non-volatile radionuclides from the waste to soil, air, and vegetation. A conceptual model describing the release scenario is presented in Figure 3.3. The conceptual model and corresponding mathematical models based on Figure 3.3 have been subdivided into three models: one for volatile radionuclides excluding radon, one for radon, and one for non-volatile radionuclides.

3.2.2.1 Conceptual Model for Volatile Radionuclides Excluding Radon

The release of gaseous species of ^{3}H, ^{14}C, and ^{85}Kr to the air above the RWMS facility was assumed to be controlled by gaseous diffusion in the air-filled pore space. Although retained for scenario development, gaseous advection was not included in the conceptual model

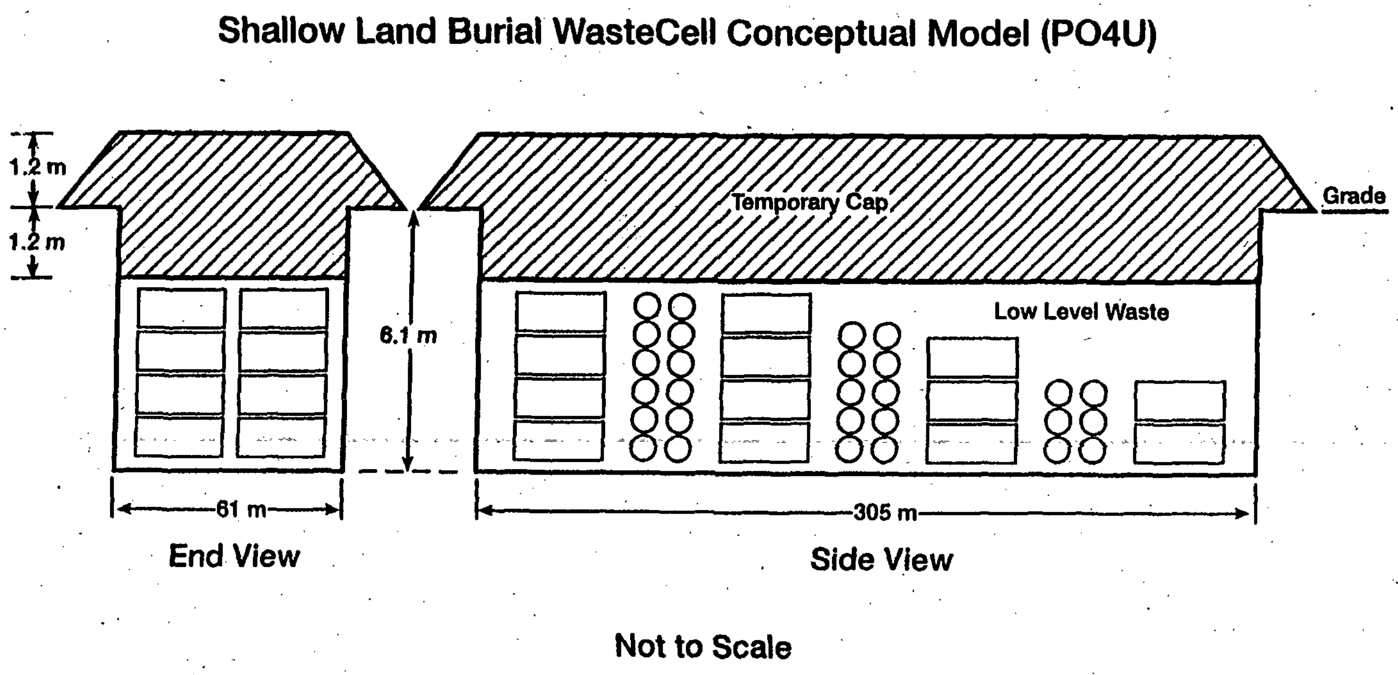


Figure 3.2 - Conceptual model of Pit 6 (PO6U) and placement of the special case thorium waste.

because it is not believed to be quantitatively significant and no codes were available to model this process. Assuming that the concentration gradient is constant over time, a conservative release rate, Q_i in Ci yr-1, can be estimated from a modified one-dimensional flux equation of the form:

$$Q_i = D_{e,i} \times \left(\frac{C_{0,i}}{z} \right) \times A \tag{3.4}$$

where:

$D_{e,i}$	=	effective diffusion coefficient of radionuclide i, in pore spaces, $m^2\ yr^{-1}$,
$C_{0,i}$	=	initial air concentration of radionuclide i in the pores of the waste zone, $Ci\ m^{-3}$,
z	=	average length of diffusion path to surface, m, and
A	=	total area of waste facility, m^2.

The expression above represents a maximum release rate because it assumes that the initial inventory is immediately available for release and that it is not significantly depleted over a year of release. Realistically, depletion due to volatilization may greatly alter the concentration in the waste during a period of one year.

To estimate $C_{0,i}$ for ^3H and ^{14}C, the chemical form of these radionuclides in the waste form must be taken into account. Tritium released to the pores of the waste form is assumed to be water vapor (i.e., HTO). This assumption is conservative because the dose conversion factor for inhalation of HTO is many orders of magnitude greater than that for HT. A significant fraction of the source term is HTO and much of the HT released will be oxidized to HTO in the soil pore water before reaching the atmosphere. Therefore, this assumption is believed to be conservative. Carbon-14 is assumed to be solely associated with gaseous CO_2 in the air-filled pores. This is a conservative assumption, because numerous carbon compounds are expected to exist in the waste and subsurface environment, all of which would compete with CO_2 for the available ^{14}C. The ^{14}C inventory received to date originates from research laboratories (Figure 2.36) and is believed to be in a relatively labile form (i.e., not activated metal).

To estimate the air concentration of HTO at the source, $C_{0,H-3}$, the concentration of ^3H in the pore water is assumed to equal its concentration in water vapor. The amount of water vapor and thus HTO vapor, in the pores is a function of temperature and relative humidity. At 100 percent relative humidity, which can be assumed for the pores due to the presence of residual water, the concentration of water vapor, $C_{V,\,H20}$ in $g.m^{-3}$, was estimated from:

$$C_{v,H_2O} = 10^3 \frac{P_v}{RT} \times MW \tag{3.5}$$

where:

10^3	=	unit conversion factor, $L\ m^{-3}$,
P_v	=	vapor pressure at given temperature, atm,
R	=	gas constant (0.082 L-atm/mol-°K),
T	=	temperature, °K , and
MW	=	molecular weight of water, 18 g mol^{-1}.

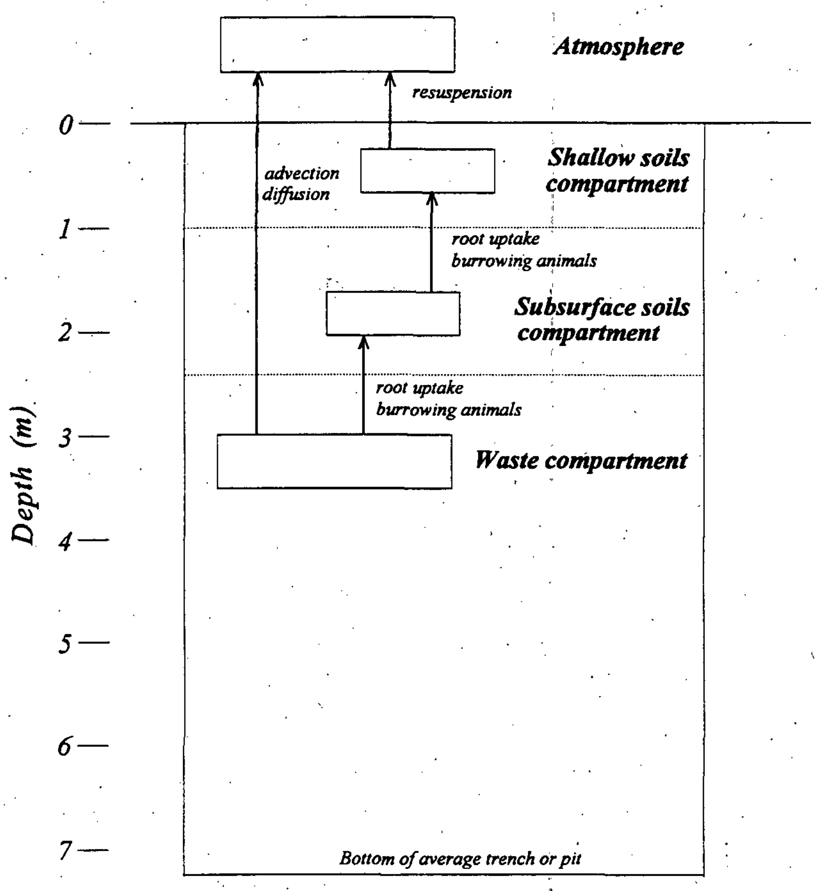


Figure 3.3 - Conceptual model of radionuclide release.

Assuming a subsurface temperature of about 283°K (10°C), corresponding to a vapor pressure of water of 1.2×10^{-2} atm (9.21 mm Hg), the concentration of water vapor in the voids is approximately 9.3 g m^{-3}.

The waste form was assumed to have a porosity and a water content equal to the values associated with alluvium to estimate the volume of water in the waste. The inventory was assumed to be diluted within this volume. Therefore, assuming a volumetric water content of 0.086 and a waste volume of approximately 3.7×10^5 m^3, there is estimated to be about 3.2×10^4 m^3 of water in the waste form.

Assuming all of the ^3H disposed of in the RWMS is initially associated with this water, an activity concentration, $C_{p,\ H\text{-}3}$, of 10 Ci m^{-3} is estimated for the pore water. This value is based on the estimated ^3H inventory at closure of 3.18×10^5 Ci (Table 3.7) and the 3.2×10^4 m^3 of water estimated in the pores. If the concentration of ^3H in pore water is equivalent to its concentration in water vapor in the pores, the air-filled pore concentration, $C_{0,H\text{-}3}$, can be calculated from:

$$C_{0,H\text{-}3} = C_{p,H\text{-}3} \times \frac{C_{v,H_2O}}{\rho_w} \tag{3.6}$$

where ρ_w is the density of water, or 10^6 g m^{-3}. The estimated ^3H concentration in the pore gas following this procedure is 9.4×10^{-5} Ci m^{-3}. The effective diffusion coefficient, $D_{e,\ H2O}$, for H_2O through the vadose zone to the ground surface was estimated as,

$$D_{e,H_2O} = D_{a,H_2O}\ 0.66\ (\varepsilon - \theta_v) \tag{3.7}$$

in soil of 136 m^2 yr^{-1}, the maximum release rate of HTO to the atmosphere at closure is estimated to be 200 Ci yr^{-1}. This is an extremely conservative value due to the simplified computational approach not accounting for the first order dependence of the release rate on the pore water concentration and the assumption that HTO diffuses through the vadose zone without further exchange of ^3H with bound water in the soil. A more complicated realistic model was not warranted as the relatively short half-life of ^3H alone depletes the source sufficiently to prevent excessive doses from ^3H at the end of institutional control. Calculation of offsite doses prior to cessation of institutional control are based on this conservative release rate.

To estimate the air-filled pore concentration of $^{14}CO_2$ at the source, $C_{0,C-14}$, all of the ^{14}C in the waste is assumed to be present in the pore gas as $^{14}CO_2$. The initial concentration of ^{14}C in the pore gas at closure is estimated to be 4.1×10^{-5} Ci m^{-3} based on a total activity at closure of 4.12 Ci (Table 3.7), a porosity of 0.36, a volumetric water content of 0.086, and a total waste compartment volume of 3.7×10^5 m^3.

The effective diffusivity of CO_2 in soil from Equation 3.7 is estimated to be 80 m^2 yr^{-1} based on a diffusivity in air of 440 m^2 yr^{-1}. From Equation 3.4, the maximum flux of ^{14}C is estimated to be 50 Ci yr^{-1} assuming the diffusion path length is 4.9 m and a waste area of 7.5×10^4 m^2. This annual release rate exceeds the initial amount of ^{14}C present in the waste at closure. Therefore, a conservative estimate of the release rate of volatile ^{14}C is 4.12 Ci yr^{-1}. This is the maximum release that could occur in any single year.

Release of ^{85}Kr, a noble gas, was assumed to occur completely within the first year after closure. As occurred with ^{14}C, annual release rate estimates based on the diffusion equation lead to estimated releases exceeding the limited initial inventory. Based on the estimated inventory of ^{85}Kr at closure (Table 3.7), the maximum release rate of ^{85}Kr is 0.0265 Ci yr^{-1} during the first year after closure. The maximum ^{85}Kr release rate decreases, by radioactive decay, to 4×10^{-5} Ci yr^{-1} by the end of institutional control. Parameters used to estimate release rates of volatile radionuclides are summarized in Table 3.10.

Table 3.10. Summary of parameters used to estimate release rates of volatile radionuclides.

Module	Parameter Description	Value Assumed	Source of Value Selected
Diffusion	$D_{a,i}$, Diffusion Coefficient in Air, $m^2\ yr^{-1}$	^3H 754 ^{14}C 440	CRC, 1981 CRC, 1981
	ϵ, Porosity of Upper Vadose Zone Soils, Dimensionless	0.36	REECo, 1993c
	θ_v, Volumetric Water Content of Upper Vadose Zone Soils, Dimensionless	0.086	REECo, 1993c

3.2.2.2 Conceptual Model for Radon Transport

Radon is a noble gas produced by the radioactive decay of radium. Three isotopes of radon, ^{219}Rn, ^{220}Rn, and ^{222}Rn, can be generated by LLW. Radon produced in buried LLW may be transported to the atmosphere by diffusion through the soil pore space and by advection of soil pore gas to the atmosphere. This section describes the conceptual model for radon transport.

Radon transport is assumed to occur within uniform regions representing the cap, buried waste, and the alluvium below the waste cell. These regions are assumed homogenous and isotropic with respect to all properties. Natural soils are a three-phase, porous medium consisting of air-filled pores, water-filled pores, and the solid soil matrix. Radon is transported to the atmosphere by molecular diffusion in the air-filled pore space and advective flow of the soil pore gas to the atmosphere (Nazaroff, 1992; Rogers and Nielson, 1991). Processes that may retard or reduce radon transport are adsorption onto solid surfaces, adsorption into the liquid phase, and radioactive decay (Nazaroff, 1992; Rogers and Nielson, 1991).

The conceptual model assumes that the fate of radon within any representative elementary volume is governed by molecular diffusion, advection, and radioactive decay in the gas phase only. Diffusion and advection of radon will be retarded in the water-filled pore space relative to the air-filled pores. Transport will be retarded further by adsorption of radon onto the solid soil matrix. Therefore, it is conservative to assume that radon transport is limited to the gas phase (Rogers and Nielson, 1991). Molecular diffusion of radon within the air-filled pore space can be represented by Fick's Law:

$$J_D = D\frac{\partial C(x,t)}{\partial x} \tag{3.8}$$

where:

J_D	=	mass flux of radon transported by diffusion, kg m^{-2} s^{-1},
D	=	diffusion coefficient of radon in soil, m^2 s^{-1}, and
C(x,t)	=	mass concentration of radon per volume of pore space, kg m^{-3}.

The flux of radon due to advection can be described by:

$$J_A = \frac{q_{air}}{\varepsilon}C(x,t) \tag{3.9}$$

where:

J_A	=	mass flux of radon transported by advection, kg m^{-2} s^{-1},
q_{air}	=	specific discharge of soil pore gas, m^3 m^{-2} s^{-1}, and
ε	=	porosity, dimensionless.

Combining the expressions for the diffusive and advective flux with production and radioactive decay gives the one dimensional equation of continuity for radon in pore spaces:

$$\frac{\partial C(x,t)}{\partial t} = D\frac{\partial^2 C(x,t)}{\partial x^2} + S_o(x) + S_{sx}(x) - \frac{1}{\varepsilon}\frac{\partial (q_{air}C(x,t))}{\partial x} - \lambda_1 C(x,t) \tag{3.10}$$

where:

$S_o(x)$	=	radon production rate per unit volume in air-filled pores of native alluvium, kg m^{-3} s^{-1},
$S_{sx}(x)$	=	radon production rate per unit volume in air-filled pores of waste, kg m^{-3} s^{-1}, and
λ_1	=	radon radioactive decay constant s^{-1}.

Advection varies in space and time with atmospheric pressure. Pressure induced changes in the specific discharge velocity can be obtained from Darcy's law:

$$q_{air} = -\frac{\kappa}{\eta}\left(\frac{\partial P}{\partial x} - \rho_{air} g\right) \tag{3.11}$$

where:

κ	=	air permeability, m^2,
η	=	air viscosity, Pascal s^1,
P	=	air pressure, Pascal s,
ρ_{air}	=	air density, kg m^{-3}, and
g	=	gravitational acceleration, m s^{-2}.

Darcy's law, the relation that $q_{air} = \varepsilon V$, where V is the advective velocity, and the ideal gas law can be combined in the mass balance expression:

$$\frac{\partial(\varepsilon \rho_{air})}{\partial t} + \frac{\partial(\rho_{air} q_{air})}{\partial x} = 0 \tag{3.12}$$

to obtain an expression for $\partial q_{air}/\partial x$ (see Lindstrom et al., 1992b).

The radon production rate in air-filled pores of waste is given by:

$$S_{sx}(x) = \frac{(1 - \varepsilon)}{\varepsilon} \frac{M_1}{M_0} \lambda_0 C_{sx}(x) \qquad (3.14)$$

where:

M_0 = atomic mass of radium, kg,
λ_0 = radium radioactive decay constant, s^{-1}, and
$C_{sx}(x)$ = radium mass concentration in waste, kg m^{-3}.

Although the conceptual model does not explicitly include an emanation coefficient, the equation for the waste source term (Equation 3.14) implies that the emanation coefficient is numerically equivalent to $(1 - \varepsilon)$.

The radon conceptual model is implemented in the CASCADR9 computer code (Lindstrom et al., 1992b; Cawlfield et al., 1993b). Briefly, continuity is assumed at the soil-atmosphere and waste-soil interfaces for radionuclide flux, radionuclide concentration, advective velocity, and barometric pressure. A 0.1 m atmospheric mixing layer is assumed to be present at the soil-air interface (Lindstrom et al., 1993a). The eddy diffusivity of the atmospheric mixing layer varies within a 24-hour period. At the soil atmosphere boundary, P(0,t) is set equal to barometric pressure values derived from a data set collected at Frenchman Flat. The barometric pressure data set consists of 730 days of measurements recorded at 15-minute intervals. Barometric data are estimated at model time steps using a Lagrange smooth cubic spline fit to 3-hour data intervals. Analysis of lengthy barometric pressure data sets have shown that radon flux reaches an nearly steady state condition after 10 to 20 days depending on the depth of burial. This can be confirmed by observing that the cumulative radon flux becomes approximately linear in 10 to 20 days. Therefore, model runs were performed with 40 days of barometric pressure data collected from Julian day 110 to 150. This period included the greatest pressure fluctuations in the data set. The average annual flux is taken as the average flux observed on day 39. The average flux is calculated as the difference in cumulative flux (pCi m^{-2}) between the end and the beginning of the 24-hour period divided by the number of seconds in 24 hours. Soil and waste radon source terms are assumed to be constant during the 40-day simulation. The model output is used to obtain a ratio between waste cell concentration and flux at the air-soil interface. Since the flux is a linear function of the waste cell concentration, flux can be predicted based on the waste cell concentration.

Parameter values used for the radon model appear in Table 3.11. The porosity and air permeability of soil are best estimate values from near surface site characterization studies (REECo, 1993c). The diffusion coefficient in soil is empirically derived from soil porosity. The porosity and air permeability of the waste are unknown and conservative values were selected.

Table 3.11. Parameters used in the radon transport model CASCADR9.

Layer	**Domain**	**Porosity** ε ($m^3\ m^{-3}$)	**Diffusion Coefficient** D ($m^2\ s^{-1}$)	**Air Permeability** κ (10^{-12} m)
Shallow Land Burial Cell				
Cap	0 to -2.4 m	0.36	2.2×10^{-6}	1
Waste	-2.4 to -7.3 m	0.67	5.5×10^{-6}	200
Special Case Thorium Waste Cell (PO6U)				
Cap	0 to -2.4 m	0.36	2.2×10^{-6}	1
Waste	-2.4 to -8.6 m	0.67	5.5×10^{-6}	200
Soil Layer	-8.6 to -12.2 m	0.36	2.2×10^{-6}	1
Th Waste	-12.2 to -15.8 m	0.67	5.5×10^{-6}	200

3.2.2.2.1 Screening of Radon Isotopes

There are potentially three isotopes of radon produced by radioactive wastes. Two isotopes, ^{219}Rn and ^{220}Rn, have half-lives less than 1 minute and can be eliminated by simple screening calculations. The USNRC has published a gaseous diffusion model for predicting attenuation

where:

J_c	=	radon flux from the soil cap, pCi m^{-2} s^{-1},
J_w	=	radon flux from the bare waste, pCi m^{-2} s^{-1},
x	=	cap thickness, m,
λ	=	radon decay constant, s^{-1},
D_c	=	radon diffusion coefficient for cap soil, m^{-2} s^{-1},
a_w	=	waste interface constant, m^{-2} s^{-1}, and
a_c	=	cap interface constant, m^{-2} s^{-1},.

The general formula for the interface constants is:

$$a = \varepsilon^2 D[1 - (1 - k)m]^2 \qquad (3.16)$$

where:

ε	=	porosity, dimensionless,
D	=	diffusion coefficient, m^{-2} s^{-1},
k	=	partition coefficient for radon gas in water, dimensionless, and
m	=	moisture saturation fraction, dimensionless.

Assuming parameter values as given in Table 3.11 for soil and waste, a partition coefficient of 0.26 (USNRC, 1989), and a saturation fraction of 0.24 (REECo, 1993c), the radon attenuation (J_c/J_w) can be calculated for several cap thicknesses (Table 3.12).

Table 3.12. Approximate attenuation of ^{219}Rn and ^{220}Rn fluxes in soil caps.

3.2.2.3 Conceptual Model for Non-Volatile Radionuclides

The release scenario includes three processes affecting non-volatile radionuclides: plant uptake, bioturbation, and resuspension of surface soil. This section summarizes the conceptual models for these processes.

3.2.2.3.1 Root Uptake Rate Coefficient

In Section 2.7, the natural flora of the NTS was described. The plant community surrounding the Area 5 RWMS is a *Larrea - Ambrosia* community characteristic of the Mohave Desert. The root uptake module incorporates parameters characteristic of this plant community when site-specific data were available.

The maximum rooting depth of native plants at the Area 5 RWMS remains uncertain. All data suggests, however, that the majority of the plant roots are in the upper 2 m. Wallace and Romney (1972) reported rooting depths less than 2 m for native plants in Mohave Desert communities on the NTS. Roots have been observed in trench walls at the Area 5 RWMS as deep as 8 m (RSN, 1991a) although it is unknown if these roots have developed since the trench wall was exposed. The presence of introduced species at the NTS contributes additional uncertainty. O'Farrell and Emery (1976) note that Russian Thistle and other introduced species have become important components of floral communities at disturbed sites on the NTS. These non-native species can inhibit the re-establishment of native plants at disturbed sites. According to Foxx et al. (1984), some forbs and shrubs found at waste disposal sites at the Los Alamos National Laboratory can have considerable rooting depths, usually averaging between 1 to 4 m. Some of the species noted in this later study also exist at the NTS. Thus, it was assumed that some fraction of the roots of the plants inhabiting Area 5 in the future may penetrate the waste. The fraction assumed (later referred to as $F_{[illegible]}$) was five percent based on the data assembled in a literature review by Foxx et al. (1984) indicating that the frequency of root penetration below 2.4 m was between 0 and 10 percent for species for which sufficient data exist.

The root uptake model (Figure 3.4) considers: (1) a waste compartment which is the original source of radionuclides for root uptake; (2) a subsurface soil compartment which is a secondary source of radionuclides for root uptake; and (3) a shallow soils compartment which becomes the source of radionuclides to the atmosphere and annual plants. The depth of the shallow soils compartment is assumed to be 1 m. This depth was chosen to be deep enough to include the roots of annual plants while minimizing dilution of radionuclides transported to the shallow soil compartment. The depth of this compartment represents the mixing depth of radionuclides transported to the surface. Mixing occurs as a result of decay of contaminated plant parts and release of radionuclides to the soil (including soil detritus) and by the action of burrowing animals.

The depth of the subsurface soil compartment, illustrated in Figure 3.4, is assumed to be 1.4 m which is the remaining depth of soil from the base of the shallow soils compartment to the top of the waste compartment. As with the shallow soils compartment, this compartment is assumed to be well mixed as a result of uptake by, and decay of, plant roots in the subsurface soil and by the action of burrowing animals.

The effective depth of the waste compartment is the depth of penetration of plant roots into the waste layer. The maximum credible rooting depth for plants occurring at Area 5 was assumed to be 4 m, based on the best available data (Foxx et al., 1984). A 4-m deep plant root would allow access to a 1.6 m layer of waste and 2.4 m of cover material (Figure 3.4). The effective depth of the waste compartment was rounded up to 2 m, giving a maximum rooting depth of 4.4 m.

The rate coefficients, $K_{r1,i}$, $K_{r2,i}$, and $K_{r3,i}$, quantify the rate of plant-mediated transfer of radionuclides from the waste to the overlying soils (Figure 3.4). These coefficients represent the fraction of radionuclides in the waste compartment that are transferred to either the shallow soils or subsurface soil compartment annually, and thus, represent fractional release rates. Estimates of these release rates were obtained by assuming that the uptake rate is directly proportional to the measured concentration ratios between plants and soils and to annual biomass production rates. Radionuclides taken up by plants each year are assumed released back to the shallow and subsurface soils compartment as a result of biomass decay. The rate coefficient describing root transport of radionuclides from the waste compartment to the shallow soils compartment, $K_{r1,i}$,, was estimated from:

$$K_{r1,i} = B_{iv} \times B_p \times \left(1+\frac{F_{rs}}{B_{ab}}\right) \times F_{rw} \times \frac{1}{H_w} \times \frac{1}{\rho_b} \qquad (3.17)$$

where:

B_{iv} = plant-soil concentration ratio for radionuclide i, pCi g^{-1} dry plant mass per pCi g^{-1} dry soil,

B_p = annual perennial shrub biomass productivity (above-ground), g dry mass m^{-2} yr^{-1},

B_{ab} = ratio of above to below ground productivity for shrubs (g yr^{-1} above ground per g yr^{-1} below ground),

F_{rs} = fraction of perennial shrub roots in shallow soils compartment, dimensionless,

F_{rw} = fraction of perennial shrubs with roots greater than 2.4 m, dimensionless,

H_w = depth of waste accessible to roots, m, and

ρ_b = dry bulk density of soil, g m^{-3}.

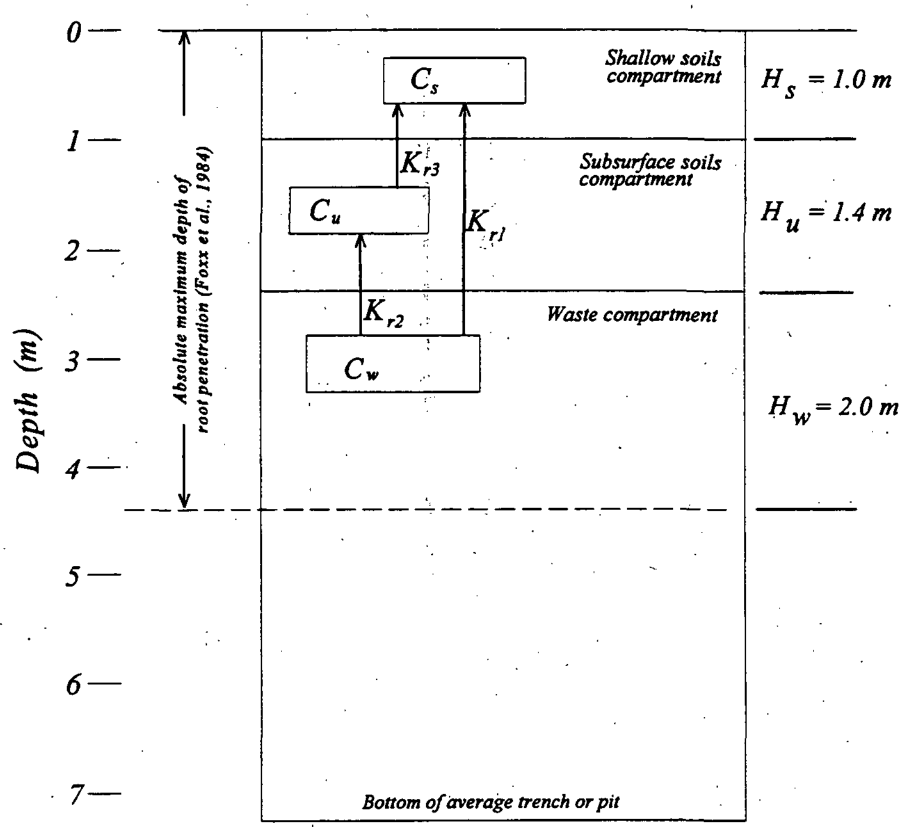


Figure 3.4 - Conceptual model of root uptake.

Baes et al. (1984) and Ng et al. (1982) were the primary sources for the plant-soil concentration ratios, B_{iv}, defined as the ratio of the concentration per dry mass of plant roots, shoots, and leaves (Ci g^{-1}) to the concentration per dry mass of soil (Ci g^{-1}). For elements with mean B_{iv} values for non-reproductive portions of crops reported by both references, the higher of the two values was adopted. The values assumed are listed in Table E.1 of Appendix E. Site-specific values were used when available, as was the case for a few radionuclides. However, most of the NTS data were collected without distinguishing between the contribution of root uptake and atmospheric deposition on plant surfaces. The later route, atmospheric deposition, is reported to be extremely important at the NTS due to easy resuspension of the exposed dry soils and xeriphytic plant adaptations (resins, hair) that effectively trap soil particulates (Gilbert et al., 1988; Romney et al., 1981). Therefore, the site-specific values assumed were selected from greenhouse studies rather than field studies, when available. Deposition of radionuclides on plants was described in a separate module described below.

The value of B_p, defined as the yearly aboveground production of plants, was assumed to be 40 g m^{-2}. This is an approximate mean value for net primary productivity for perennial shrubs in the vicinity of Area 5, discussed in Section 2.7.1.

The ratio of aboveground to below ground productivity, B_{ab}, was estimated from biomass distribution between roots and shoots. Root productivity data were not available for the shrub communities of interest. Using the root-to-shoot biomass ratios requires the assumption that biomass ratios are similar to productivity ratios for above and below ground biomass. While quite variable between species, time of year, and age of plants, the biomass ratio between roots and shoots varies between about 0.6 and 2.3 for vegetation native to the Mohave Desert (Wallace et al., 1974). A representative mid-range value of 1.0 was assumed for B_{ab}.

The fraction of vegetation with roots which penetrate into the waste compartment, F_{rw}, and the maximum depth of the waste compartment that may be penetrated by roots, H_w, were discussed earlier and were assigned respective values of 0.05 and 2 m. The dry bulk density assumed for soil and waste is 1.6×10^6 g m^{-3} based on data collected in the Science Trench Borehole study (REECo, 1993c).

Plant roots not penetrating the waste compartment were assumed to be uniformly distributed in the cap. This assumption is made in lieu of site-specific data for vertical distribution of root biomass of native or introduced species at the NTS. Therefore, the fraction of perennial shrub roots assumed present in the shallow soils compartment, F_{rs}, is 0.42. The value of 0.42 is based on the assumed 1-m depth of the shallow soils compartment relative to the total 2.4-m depth of the overlying soil column.

The coefficient K_{r2} represents the transfer of radionuclides from the waste compartment to the subsurface soil compartment. This coefficient is estimated from:

$$K_{r2,i} = B_{iv} \times \frac{B_p}{B_{ab}} \times F_{ru} \times F_{rw} \times \frac{1}{H_w} \times \frac{1}{\rho_b} \qquad (3\text{-}18)$$

where F_{ru} is the fraction of deep-rooted shrub roots in the subsurface soils compartment. The fraction of shrub roots in the subsurface soils compartment, F_{ru}, is obtained from:

$$F_{ru} = 1 - \left(F_{rs} + F_{rw} \right) = 1 - 0.47 \qquad (3\text{-}19)$$

and thus is equal to 0.53.

The variable K_{r3} represents the transfer of radionuclides by root uptake to shallow soils from subsurface soils and is calculated from:

$$K_{r3,i} = B_{iv} \times B_p \times \left(1 + \frac{F_{rs}}{B_{ab}} \right) \times F_{ru} \times \frac{1}{H_u} \times \frac{1}{\rho_b} \qquad (3\text{-}20)$$

where H_u is the depth of the subsurface soil compartment. The value of H_u was assumed to be 1.4 m, as discussed above.

Values of the fractional release rates $K_{r1,i}$, $K_{r2,i}$, and $K_{r3,i}$, which are radionuclide-specific, are listed in Table E.2 of Appendix E.

3.2.2.3.2 Burrowing Animal Rate Coefficient

Several species of burrowing animals, most importantly ants and rodents, are found at the Area 5 RWMS. The rate coefficients K_{b1} and K_{b2} (Figure 3.5) represent the movement of radionuclides to shallow soils and subsurface soils, respectively, as a result of the activities

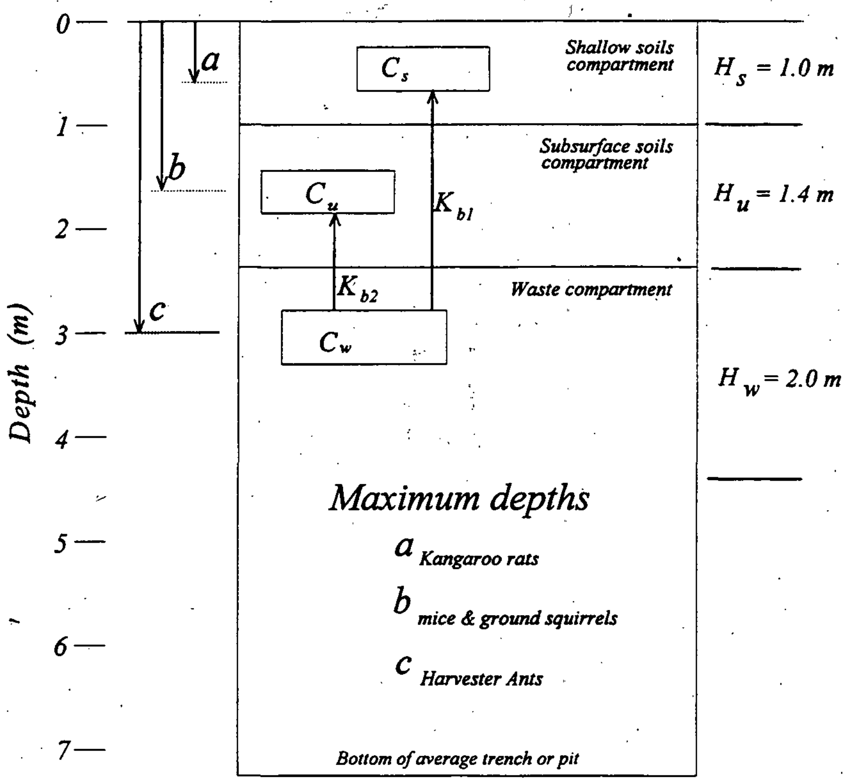


Figure 3.5 - Conceptual model of burrowing animal transport.

of burrowing animals. These transfer coefficients are pertinent only to burrowers that excavate soil as deep as the waste compartment which at facility closure is at least 2.4 m deep.

Among the burrowers present on the NTS, only ants and possibly termites are expected to burrow to depths in excess of 2.4 m. In lieu of any data on termite burrows, only the excavation potential of ants was considered in this assessment. Parameters selected for the ant model are conservative and should compensate for the lack of a specific termite model. Harvester ants are reported to burrow to depths of 2 to 3 m (Fitzner et al., 1979; Blom et al., 1991a). Harvester ants occur on the NTS but there is no data specific to the NTS. Although other burrowers, predominantly rodents, exist in Area 5 (Section 2.7.2), the burrows tend to be shallow relative to those of ants and to the depth of the waste form. As indicated in Table 2.13, the rodent population near the Area 5 RWMS is reported to include kangaroo rats, a few species of mice, and ground squirrels with densities ranging from 5×10^{-6} to 3×10^{-3} individuals m^{-2}. Anderson and Allred (1964) report that kangaroo rats burrow no deeper than 0.6 m at the NTS and burrow depths for kangaroo rats, mice, and ground squirrels at the Idaho National Engineering Laboratory (INEL) are reported to be less than 1.4 m (Reynolds and Laundré, 1988; USDOE, 1983). Thus, the actions of burrowers other than ants are assumed to redistribute the soil within compartments, and are not considered explicitly in the conceptual model for burrowing animals. Movement of soil between the shallow and subsurface soil compartments was not considered.

The rate coefficient K_{b1} represents the transfer of radionuclides from the waste to the shallow soil compartment through the actions of burrowing ants. The amount of excavated soil transferred to the shallow surface soil compartment is assumed to be proportional to the depth of the shallow soil compartment relative to the depth of the cover. The value of K_{b1} can be calculated from:

$$K_{bl} = \frac{1}{\rho_b} \times A_b \times D_d \times \frac{1}{H_w} \times \frac{H_s}{H_u + H_s} \tag{3-21}$$

where:

A_b	=	amount of soil excavated by each ant colony in the waste zone, g yr^{-1},
D_d	=	density of burrower (ant colony) that burrows as deep as the waste zone, colonies m^{-2}, and
H_s	=	average depth of the shallow soils compartment, m.

The values of ρ_b, H_w, and H_u are the same as were used in the derivation of transfer coefficients for root uptake.

According to Fitzner et al., (1979), the amount of soil excavated by an individual harvester ant colony at the Hanford site ranged from 7.1×10^{-4} to 3.1×10^{-3} m^3 over the life of the colony. Assuming a bulk soil density of 1.6×10^6 g m^{-3}, this corresponds to a range of 1.1×10^3 to 5.0×10^3 g soil moved. Fitzner et al., (1979) also reports an average of 3.8×10^3 g of soil was excavated by harvester ants in eastern Colorado over the life of the colony. With this information, a value of A_b can be estimated if an estimate of the life of the colony can be obtained. Blom et al., (1991b) reports that harvester ant species may persist for 17 to 50 years based on data from other locations in the Midwest. Because this value is likely to vary considerably from location to location, a conservative value of 10 years was assumed to obtain a conservative estimate of A_b from the Fitzner et al., (1979) data. Assuming the maximum soil movement per colony observed by Fitzner et al., (1979) (5.0×10^3 g per life-time) and a 10-year life-time, an estimate of A_b of 5.0×10^2 g yr^{-1} is obtained. Before finalizing the estimate for A_b, the fraction of ant burrows occurring in the waste zone must be considered. Fitzner et al., (1979) estimates that 11 percent of soil excavated by ants comes from depths greater than 1.5 m although the source of data supporting this estimate is unclear. The value of A_b used in the assessment, 100 g yr^{-1} excavated per colony, assumes that 20 percent of the soil excavated by a colony comes from a depth greater than 2.4 m.

Harvester ant colony density, D_d, has been reported by Fitzner et al., (1979) at the Hanford site, and Blom et al., (1991a) at INEL, to range from 0 to 1.6×10^{-2} colonies m−2.

An average density of 1×10^{-2} colonies m^{-2} was assumed for this assessment. In the equation for K_{b1}, the ratio of the depth of the shallow soils compartment, H_s, to the total depth of the soil column above the waste ($H_u + H_s$) partitions the amount of excavated contaminated soil equally between the two soil compartments on a per volume basis, as was noted earlier.

The parameter K_{b2} represents the transfer of radionuclides from the waste to the subsurface soils as a result of ant burrows constructed in the waste. Again, in the equation for K_{b2}, below, the ratio of the depth of the subsurface soils compartment, H_u, to the total depth of the soil column above the waste ($H_u + H_s$) allows partitioning of the amount of excavated contaminated soil equally between the two soil compartments on a per volume basis. The transfer rate coefficient K_{b2} was calculated as:

$$K_{b2} = \frac{1}{\rho_b} \times A_b \times D_d \times \frac{1}{H_w} \times \frac{H_u}{H_u + H_s} \qquad (3\text{-}22)$$

The calculated value of K_{b1}, estimating the fractional annual release rate of any radionuclide, from the waste to the shallow soils compartment, is 1.3×10^{-7} yr^{-1}. The calculated value of K_{b2}, estimating the fractional annual release rate of any radionuclide from the waste compartment to the subsurface soils compartment, is 1.8×10^{-7} yr^{-1}.

3.2.2.3.3 Resuspension Coefficient

Contamination of air above the RWMS facility may occur as volatile radionuclides are released, as discussed in the previous section, or when contaminated shallow surface soils are suspended and resuspended by the wind. The rate constant for the resuspension module, representing the fractional average annual loss of radionuclide from the shallow soils compartment, is estimated from a review by Layton et al., (1993) of calculated resuspension rates for the NTS based on $^{239,240}Pu$ data. The assumed value of the resuspension rate for this module is 1×10^{-4} yr^{-1}, selected from a range of 3.15×10^{-5} to 3.15×10^{-4} yr^{-1}.

3.2.2.3.4 Summary of Release Scenario and Conceptual Model for Non-Volatile Radionuclides

The release scenario retained five processes thought to transport radionuclides to the accessible environment. The processes were: diffusion of gases, advection of gases, plant uptake, burrowing animal transport, and resuspension. The previous sections describe the development of rate coefficients for the conceptual model of non-volatile radionuclide

Table 3.13. Parameters used to estimate transfer rate coefficients for non-volatile radionuclides.

Module	Parameter Description	Value Assumed	Source
Root Uptake	B_{ab}, Ratio of Above to Below Ground Productivity for Shrubs, g yr^{-1} above per g yr^{1} below	1	Wallace et al., 1974
	B_{iv}, Radionuclide-Specific Plant-Soil Concentration Ratio	Table E.1	see Table E.1
	B_p, Annual Perennial Shrub Biomass Productivity (aboveground) g dry wt m^{-2} yr^{-1}	40	Romney and Wallace, 1979 Banberg et al., 1976 Strojan et al., 1979
	F_{rs}, Fraction of Perennial Shrub Roots in the Shallow Soils Compartment	0.42	Based on Assumption that Root Mass Evenly Distributed to 2.4 m Depth
	F_{ru}, Fraction of Perennial Shrub Roots in the Subsurface Soils Compartment	0.53	Based on Assumption that Root Mass Evenly Distributed to 2.4 m Depth
	F_{rw}, Fraction of Perennial Shrubs with Roots >2.4 m	0.05	Foxx et al., 1984
	H_s, Depth of the Shallow Soils Compartment, m	1	Depth Chosen to Represent Maximum Rooting Depth of Annuals
	H_u, Depth of the Subsurface Soils Compartment, m	1.4	Based on Selected Value of H_s, and Soil Cover Depth of 2.4 m
	H_w, Depth of the Waste Accessible to Roots and Burrowing Animals, m	2	Foxx et al., 1984
	ρ_b, Bulk Density of Soil, g m^{-3}	1.6×10^6	REECo, 1993c
Burrowing Animals	A_b, Amount of Soil Excavated by Each Ant Colony in the Waste Zone, g yr^{1}	100	Fitzner et al., 1979
	D_d, Density of Ant Colonies, colonies m^{-2}	0.01	Blom et al., 1991a Fitzner et al., 1979
Resuspension	K_s, Resuspension Rate, yr^{1}	10^{-4}	Layton et al., 1993

Values of the radionuclide specific root transfer coefficients are given in Table E.2 of Appendix E. The values of K_{b1} and K_{b2} are 1.3×10^{-7} yr^{-1} and 1.8×10^{-7} yr^{-1}, respectively. The radioactive decay constants, $\lambda_{r,i}$, are given in Table E.3, and the assumed value of K_s was 10^{-4} yr^{-1}.

The transfer rates of radionuclides associated with root uptake, excavation by burrowing animals, and suspension of contaminated shallow soils in air were used to estimate concentrations in the soil and waste compartments. The equation describing the total activity of radionuclide i in shallow soil can be written as:

$$\frac{dA_{s,i}}{dt} = A_{s,i} \times \left(-K_s - \lambda_{r,i} \right) + A_{w,i} \times \left(K_{r1,i} + K_{b1} \right) + A_{u,i} \times K_{r3,i} + A_{s,i-1} \times B_i \times \lambda_{r,i} \qquad (3.23)$$

where:

$A_{s,i}$	=	activity of radionuclide i in shallow soils, Ci,
$A_{s,i-1}$	=	activity of parent radionuclide (i - 1) in shallow soil, Ci,
$A_{u,i}$	=	activity of radionuclide i in subsurface soil, Ci,
$A_{w,i}$	=	activity of radionuclide i in waste accessible to biointruders, Ci,
B_i	=	branching ratio from parent to radionuclide i, dimensionless,
$K_{r1,i}$	=	fractional root uptake rate for radionuclide i from the waste compartment to the shallow soils, yr^{-1},
$K_{r3,i}$	=	fractional root uptake rate for radionuclide i from the subsurface soil compartment to the shallow soils, yr^{-1},
K_{b1}	=	fractional transfer rate for radionuclides from the waste compartment to the shallow soils, based on burrowing animal activity (radionuclide-independent), yr^{-1},
$\lambda_{r,i}$	=	radioactive decay constant for radionuclide i, yr^{-1}, and
K_s	=	resuspension rate, yr^{-1}.

The concentration of radionuclide i in the shallow soils compartment, $C_{s,i}$, is estimated by dividing that compartment's total activity by the product of its volume and the soil density. The volume of the shallow soils compartment, V_s, is the surface area of all trenches and pits (7.5×10^4 m^2) multiplied by the 1-m depth of that compartment, or 7.5×10^4 m^3. The soil density, ρ_b, of the upper vadose zone at Area 5 is assumed to be 1.6×10^6 g m^{-3} (REECo, 1993c).

The equation describing the total activity in the subsurface soil compartment, $A_{u,i}$, is:

$$\frac{dA_{u,i}}{dt} = A_{u,i} \times (-K_{r3,i} - \lambda_{r,i}) + A_w \times (K_{r2,i} + K_{b2}) + A_{u,i-1} \times B_i \times \lambda_{r,i} \qquad (3.24)$$

where $K_{r2,i}$ is the fractional root uptake rate of radionuclide i from the waste compartment to the subsurface soils, K_{b2} is the fractional transfer rate for radionuclides from the waste compartment to the subsurface soils as a result of burrowing animal activity, and $A_{u,\,i-1}$ is the activity of the parent of radionuclide i in the subsurfaces soil compartment.

The equation describing total activity in the accessible waste compartment, $A_{w,i}$, is:

$$\frac{dA_{w,i}}{dt} = A_{w,i} \times (-\lambda_{r,i} + -K_{r1,i} + -K_{r2,i} + -K_{b1} + -K_{b2}) + A_{w,\,i-1} \times B_i \times \lambda_{r,i} \tag{3.25}$$

where $A_{w,\,i-1}$ is the activity of the parent of radionuclide i in the waste compartment. The initial activity in the accessible waste compartment is the total inventory which is accessible [illegible]

(Table 3.7). The initial activity of each radionuclide in the accessible waste compartment was estimated by multiplying the estimated mean activity concentrations at closure (Table 3.7) by the assumed volume of accessible waste, which is 1.5×10^5 m^3, based on an waste area of 7.5×10^4 and a depth of 2 m. The 2-m depth is the maximum depth into the waste compartment that roots or burrowing animals are assumed to reach.

Two scenarios were identified in Section 3.1.2: (1) a transient occupation scenario and (2) an open rangeland scenario with an offsite resident. To estimate exposure to individuals according to these scenarios, environmental concentrations were estimated based on the release rates to the accessible environment which were calculated as described in the previous sections. The following two sections describe the methodology used to calculate doses based on the estimated surface soil concentrations.

3.2.3.1 Transient Occupation Scenario

The transient occupation scenario describes potential human exposures to radionuclides released from the RWMS to the accessible environment immediately above the facility. This scenario does not begin until 100 years after closure because it is assumed that active institutional control will exclude members of the public from the site for at least 100 years.

The transient occupation scenario assumes that members of the public may be present at the site, but do not permanently reside at the site or engage in agricultural activities. Review of

where:

$C_{g,i}$ = activity concentration of gaseous radionuclide i, Ci m^{-3},
Q_i = activity release rate, Ci yr^{-1},
H_{mix} = mixing zone height, m,
U = mean wind speed, m yr^{-1} and,
A = area of release, m^2.

The mean wind speed was assumed to be 2 m s^{-1} and the area of release was the area of the pits and trenches, 7.5×10^4 m^2. The mixing height was conservatively assumed to be 2 m. Calculation of the release rate was described in Section 3.2.2.1.

Methods for calculating the activity concentration of non-volatile radionuclides in soil were described in the previous section. The concentration of particulate radionuclides in air were calculated by a mass loading approach where the resuspended activity is estimated based on the assumed mass loading of particulates in air. The concentration of radionuclide i in air above the facility, $C_{a,i}$, in Ci m^{-3}, is related to its shallow soil activity, $A_{s,i}$, in Ci, by:

$$C_{a,i} = \frac{A_{s,i}}{V_s \rho_b} \times M_s \times E_f \qquad (3.27)$$

where M_s is the mass loading of soil particulates in air, g m^{-3}, and E_f is defined as the enrichment factor, which is dimensionless. A value of 10^{-4} g m^{-3} was assumed for the mass loading parameter, M_s. This value is higher than the annual mean concentrations reported by the National Air Surveillance Network for 30 non-urban sites across the United States in 1964 and 1965 (USEPA, 1990). These values range from less than 1×10^{-5} to 6×10^{-5} g m^{-3}. Isopleths generated from data from the 30 sites indicate annual mean values for the state of Nevada ranging between 6×10^{-5} to 2×10^{-5} g m^{-3} for those two years. Because mass loading in the vicinity of Area 5 can only be estimated with the regional isopleths, making the uncertainty in the estimate difficult to quantify, the conservative value of 10^{-4} g m^{-3} was ultimately chosen.

The enrichment factor, E_f, is used to correct for non-uniform concentration among various soil particle size groups. An enrichment factor greater than one indicates that the radionuclides are more concentrated on the resuspendable size fractions (i.e., the concentration of radionuclides on suspended soil is greater than the average concentration over all particle sizes) while a factor less than one indicates that enrichment occurs among less mobile fractions. According to Layton et al., (1993), enrichment factors for plutonium

In addition to the conservative mass loading factor of 10^{-4} g m^{-3}, an additional source of conservatism in the mass loading model is the absence of a correction for area size. The model described by the equation for mass loading does not consider the dilution of the resuspended radionuclides by uncontaminated dust upwind of the Area 5 RWMS. Rather, the model assumes that the source area is sufficiently large to negate such dilution effects. The amount of conservatism added by this assumption is a function of the ratio of the particle deposition velocity to the wind speed, the distance from the receptor to the nearest and furthermost edges of the source area, and meteorological parameters pertinent to stability (USEPA, 1990).

Solution of Equations 3.23 through 3.27 allows estimation of concentrations in air and soil, important to the assessment of the TEDE to a transient occupant of the Area 5 RWMS following the institutional control period. The TEDE values were calculated from these concentrations in the following manner.

First, external effective dose equivalent and CEDE from inhalation of non-volatile radionuclides was calculated for the maximum soil concentration to evaluate an upper bound on the dose and to screen out radionuclides that contribute less than 0.1 percent of the 25 mrem yr^{-1} dose limit for the all pathways analysis. Maximum external dose, $D_{i,max}^{ext}$ in mrem yr^{-1}, was calculated for each radionuclide from:

$$D_{i,\max}^{ext} = \frac{A_{s,i}^{\max}}{V_s} \times DCF_i^{ext} \times \frac{2000}{8760} \qquad (3.28)$$

where DCF_i^{ext} is the effective external dose rate conversion factor for radionuclide i, in mrem yr^{-1} per Ci m^{-3} in soil, based on a continuous exposure throughout the year. The factor 2000/8760 corrects for the reduced exposure time for transient occupancy. In this case, it is assumed that the occupant is onsite for 2,000 hours per year. Since time spent onsite is highly uncertain, a bounding value was selected. No dilution by clean soil in between trenches and pits is assumed. The distribution of the source with depth is accounted for in Equation 3.28 through the selection of values for DCF_i^{ext}. Values for DCF_i^{ext} were taken from an USEPA Federal Guidance Report No. 12 (Eckerman and Ryman, 1993) which lists dose conversion factors for exposure to soil contaminated to various depths. The values selected assume that the contamination is distributed to infinite depth (see Table E.3). Since the shallow soil compartment is 1 m deep in this model, assuming an infinite depth of contamination is conservative. Radioactive progeny that could be assumed to be in equilibrium with the parent were accounted for by adding the dose conversion factor of the progeny to that of the parent.

Maximum inhalation doses from particulate radionuclides were calculated from:

$$D_{i,\max}^{inh} = 1920 \times DCF_i^{inh} \times C_{a,i} \tag{3.29}$$

where DCF_i^{inh} is the CEDE conversion factor for inhalation of radionuclide i (USDOE, 1988c) and the number 1,920 represents the annual volumetric intake of air by inhalation, in $m^3\ yr^{-1}$, for a transient occupant assumed to be at the Area 5 RWMS for 2,000 hours per year.

For gaseous radionuclides, the dose was calculated as:

$$D_{i,\max}^{gas} = 1920 \times DCF_i^{inh} \times C_{g,i} \tag{3.30}$$

The dose equivalent from radionuclides listed in Table 3.5 in italics were calculated using Equation 3.29 and 3.30. The dose conversion factor, DCF_i^{inh}, includes the dose from all progeny produced within the body. A few of the italicized radionuclides in Table 3.5 have progeny with sufficiently long half-lives and retention times that the dose from inhalation of the progeny is a significant fraction of the dose from the parent. In these cases, the progeny were assumed in equilibrium with the parent and the DCF_i^{inh} of the progeny were added to the value for the parent. Radionuclide dose conversion factors corrected in this fashion were those for ^{93}Zr, ^{126}Sn, ^{210}Pb, ^{227}Ac, ^{229}Th, and ^{237}Np. The ^3H dose conversion factor was correct by a factor of 1.5 to account for dermal absorption. Values of dose conversion factors used are listed in Table E.3.

The bounding dose calculations for the transient occupant scenario, based on maximum soil concentrations, indicated that 9 radionuclides (^{226}Ra, ^{227}Ac, ^{228}Th, ^{230}Th, ^{231}Pa, ^{234}U, ^{235}U, ^{238}U, and ^{239}Pu) contributed greater than 0.025 mrem yr^{-1} each to a transient occupant. Only these radionuclides were considered in subsequent dose estimates. For these more significant radionuclides, doses were calculated based on the time-dependant soil and air concentrations generated by solution of Equations 3.23 through 3.25. The results of the calculations performed, in terms of peak dose and 10,000-year dose (if the peak occurs after 10,000 years), for each radionuclide are provided in Section 4.1.

3.2.3.2 Open Rangeland Scenario

The open rangeland scenario assumes that a ranch is or will be established at an offsite location with available water after closure of the RWMS. The locations nearest the RWMS with available water are Indian Springs which is outside of the current NTS boundary, approximately 42 km to the southeast, and Cane Springs which is within the current NTS boundary, approximately 14.3 km to the southwest.

Exposure pathways for offsite members of the public include atmospheric transport of volatile or suspended radionuclides from the RWMS, deposition of atmospheric radionuclides on soil and crops at the location of the residence, and transfer of radionuclides from native vegetation and soil at the RWMS to milk and beef from cattle grazing onsite. During the period of institutional control, pathways involving the grazing of cattle over the facility are not considered.

A complete list of the pathways in the conceptual model for the open rangeland scenario is provided in Table 3.2 and Figure 3.7. All of these pathways, with the exception of those for


RWMS

The external contamination of vegetation from deposition of suspended radionuclides on the stems and leaves of plants is estimated from:

$$C_{v,i}^{ext} = \frac{V_d \times F_v}{\lambda_w} \times C_{a,i} \tag{3.32}$$

where:

$C_{v,i}^{ext}$	=	external concentration of radionuclide i on vegetation, Ci g^{-1},
V_d	=	deposition velocity, m yr^{-1},
F_v	=	foliar interception factor, m^2 g^{-1} dry vegetation,
λ_w	=	weathering constant, yr^{-1}, and
$C_{a,i}$	=	suspended air concentration of radionuclide i over the cover soil, Ci m^{-3}.

Equations 3.31 and 3.32 are similar to equations used in the USNRC Regulatory Guide 1.109 (USNRC, 1977) and by Martin and Bloom (1980) for predicting contamination of vegetation but assume that plant growth and radioactive decay do not decrease the radionuclide concentration in the vegetation.

The deposition velocity in Equation 3.32, V_d, is assumed to be 6.3×10^4 m yr^{-1} (0.2 cm s^{-1}). This value strongly depends on wind speed and particle size (Martin and Bloom, 1980). Baes et al., (1984) assume a value of 3.2×10^4 m yr^{-1} for coarse suspended matter, citing data by Sehmel (1980).

The foliar interception fraction, F_v, is assumed to be 10^{-3} m^2 g^{-1}, a conservative value based on a review of data by Martin and Bloom (1980) specific to the NTS, indicating a mean of about 4×10^{-4} m^2 g^{-1}, with a maximum value of 1.1×10^{-3} m^2 g^{-1}. The weathering rate, representing the effective rate of loss of radionuclides deposited on plant surfaces, λ_w, is assumed to be 18 yr^{-1}. This is the default value used in the USNRC Regulatory Guide 1.109. The value of 18 yr^{-1} corresponds to a weathering half-time of 14 days. Martin and Bloom (1980) suggest that the weathering half-time increases as a function of time, beginning at a value of around 1 day and increasing to a value more than two orders of magnitude higher for remaining surficial contamination. However, this type of weathering model was considered too complex to be supported by the data available, and thus, the default value of 14 days was adopted.

The concentration in air above the cover soil, $C_{a,i}$, was calculated according to Equation 3.27, using the mass loading approach. Values of $A_{s,i}$ were calculated as in Equation 3.23, above.

The open rangeland scenario requires an estimate of radionuclide concentrations in beef and milk from cattle grazing over the Area 5 RWMS. These concentrations were calculated in a manner similar to that used in the USNRC Regulatory Guide 1.109. However, radioactive decay occurring between ingestion of forage and consumption of milk or beef was neglected, because the radionuclides in Table 3.7 are long-lived relative to hold-up times.

The small area of the RWMS and low productivity of Mohave Desert rangeland combine to limit the grazing potential. In Section 2.6, the number of animal unit months (AUM) per hectare for cattle grazing on native vegetation on Frenchman Flat was estimated to be 0.07 based on considerations of standing biomass and generic forage ingestion rates. Assuming a total contaminated area of 7.5×10^4 m^2, the site represents about 1 AUM. That is, one cow could be sustained by natural forage on the site for one month. Rather than account for the potentially non-steady state conditions that would arise for livestock grazing for one or two months on the site, it was assumed that contaminated beef and milk were available year round to the offsite residents. The radionuclide concentration in the beef and milk represents the steady state concentration for livestock grazing continuously on contaminated areas. It should be emphasized that this is an extremely conservative assumption made to simplify computations.

For milk, the concentration of radionuclide i, $C_{m,i}$ in Ci kg^{-1}, is estimated from:

$$C_{m,i} = F_{m,i} \times \left(I_v \times C_{v,i} + I_s \times \frac{A_{s,i}}{V_s \times \rho_b} \right) \tag{3.33}$$

where:

$F_{m,i}$	=	fraction of daily ingested radionuclide i found in milk, day kg^{-1} milk,
I_v	=	contaminated forage ingestion rate of cattle, g dry plant day^{-1},
$C_{v,i}$	=	concentration of radionuclide i in forage vegetation, Ci g^{-1} dry plant,
I_s	=	contaminated soil ingestion rate of cattle, g dry soil day^{-1},
$A_{s,i}$	=	activity of radionuclide i in shallow soil compartment, Ci,
V_s	=	volume of the shallow soils compartment, m^3, and
ρ_b	=	dry bulk density of soil, g m^{-3}.

The concentration in vegetation, $C_{v,i}$ is the sum of $C_{v,i}^{ext}$ and $C_{v,i}^{inh}$ from Equations 3.31 and 3.32. Values of $F_{m,i}$ (Table E.1) were adopted from a compilation of these values by Baes et al., (1980) for all radionuclides except ^3H and ^{14}C, which were not available in that document. Values of $F_{m,i}$ for ^3H and ^{14}C were obtained from the USNRC Regulatory Guide 1.109, Revision 1 (USNRC, 1977), which provided values based on specific activity considerations for these radionuclides.

The assumed forage consumption rate of cattle grazing on native flora at the Area 5 RWMS, I_v, was 8 kg dry vegetation day^{-1}, based on a review of site-specific and desert forage consumption studies for cattle by Martin and Bloom (1980). The assumed soil consumption rate, I_s, is 0.5 kg dry soil day^{-1}, based on reports by Martin and Bloom (1980) and Smith (1977).

For beef, the concentration of radionuclide i, $C_{b,i}$, in Ci kg^{-1}, is calculated from:

$$C_{b,i} = F_{b,i} \times \left(I_v \times C_{v,i} + I_s \times \frac{A_{s,i}}{V_s \times \rho_b} \right) \tag{3.34}$$

where $F_{b,i}$ represents the fraction of the cow's daily ingestion of radionuclide i that is transferred to muscle, in day kg^{-1}. Values of $F_{b,i}$ (Table E.1) were taken from a review by Baes et al., (1980) for all radionuclides except ^3H and ^{14}C. Values of $F_{b,i}$ for ^3H and ^{14}C were obtained from the USNRC Regulatory Guide 1.109, Revision 1 (USNRC, 1977), which provided values based on specific activity considerations for these radionuclides. Other parameters in Equation 3.34 are defined above.

3.2.3.3 Radionuclide Screening

Evaluation of offsite concentrations of radionuclides in air and crops to which residents might be exposed requires that atmospheric transport to the residence locations be simulated. Because of the considerable dilution accompanying this mode of transport, screening calculations were carried out to eliminate radionuclides from Table 3.7 which do not cause a significant dose relative to the all pathways dose limit of 25 mrem yr^{-1}. These screening calculations were carried out assuming no dilution of the air or soil above the facility. Screening dose calculations were evaluated for the peak shallow soil concentrations of each radionuclide, since all environmental concentrations are ultimately tied to this concentration. Estimated doses which were judged to be significant, or contributing at least 0.025 mrem yr^{-1} under the conservative conditions defined, were re-evaluated with a more realistic of contaminated vegetation, milk, soil, and beef (D_i^{ing}) was calculated from:

$$D_i^{ing} = DCF_i^{ing} \times \left[U_v \left(C_{v,i}^{int} + C_{v,i}^{ext} \right) + U_s \frac{A_{s,i}}{V_s \ \rho_b} + U_m C_{m,i} + U_b C_{b,i} \right] \tag{3.35}$$

where U_v, U_s, U_m, and U_b are intake rates of vegetation (g dry yr^{-1}), soil (g yr^{-1}), milk (kg yr^{-1}), and beef (kg yr^{-1}), respectively. The DCF_i^{ing} is the CEDE conversion factor for ingestion of radionuclide i (USDOE, 1988b). Values used for DCF_i^{ing} are listed in Table E.3. The ingestion CEDE conversion factors were corrected for progeny, as described for inhalation exposures. The assumed intake rates for vegetation, milk, and beef are given in Table 3.14. Ingestion rates for fruits and vegetables were available on a fresh mass basis only. To convert wet mass vegetation intake, U_v, to dry mass, an average dry-to-wet mass ratio of 0.2 (Baes et al., 1984) was assumed, giving a U_v of 32 kg dry yr^{-1}. Ingestion of soil by humans, assumed to occur inadvertently with ingestion of incompletely washed vegetation, is estimated to be about 40 g yr^{-1} (USEPA, 1989).

Table 3.14. Assumed values of dietary intake (from Rupp, 1990).

Product Consumed	Estimated Intake for Adults (Wet Mass)
Vegetables, Potatoes, Fruit	160 kg yr^{-1}
Milk and Milk Products (Ca equivalent)	220 kg yr^{-1}
Beef	30 kg yr^{-1}

Doses calculated using the screening method described above lead to the retention of 16 radionuclides for more detailed analysis. These 16 radionuclides include all of the nuclides retained in the transient occupancy scenario. This could be expected because external and inhalation exposures were calculated for both scenarios in a similar manner. The additional radionuclides include three volatile radionuclides (^{3}H, ^{14}C, ^{85}Kr) and two nuclides important in ingestion pathways (^{237}Np and ^{241}Am). The final list of radionuclides for the open rangeland scenario with the offsite resident consists of: ^{3}H, ^{14}C, ^{85}Kr, ^{210}Pb, ^{226}Ra, ^{227}Ac, ^{228}Ra, ^{228}Th, ^{230}Th, ^{231}Pa, ^{234}U, ^{235}U, ^{237}Np, ^{238}U, ^{239}Pu, and ^{241}Am.

3.2.3.4 Full Pathway Analysis for the Open Rangeland Scenario

The nuclides retained from the screening analysis were carried through a full pathway analysis with atmospheric dispersion to the location of the offsite resident. For volatile ^{3}H, ^{14}C, and ^{85}Kr, atmospheric transport calculations were performed to estimate air, soil, and vegetation concentrations at the ranch location. Release rates estimated for ^3H, ^{14}C, and ^{85}Kr, in Section 3.2.2.1, provided source terms for atmospheric transport. Offsite air concentrations, $C_{ax,i}$, were estimated for these source terms using CAP88-PC (USEPA, 1992), an USEPA-sanctioned code developed for estimating TEDE to members of the public resulting from radionuclide emissions to air. Site-specific atmospheric conditions available for Frenchman Flat were used for the computations, and the source was assumed to be an area source of 7.5×10^4 m^2. Air concentrations at Indian Springs (42 km southeast of Area 5) were calculated. Volatilization is assumed to occur immediately after facility closure during the period of institutional control. Because Cane Springs, 14.3 km south-southwest of Area 5, is within the NTS boundary, air concentrations of volatile forms of ^3H, ^{14}C, and ^{85}Kr are not calculated at this location for the period of institutional control.

Concentrations of ^3H and ^{14}C in soil at the offsite location ($C_{sx,i}$ in Ci m^{-3}) were calculated using the deposition velocity, V_d, introduced in Equation 3.32. Krypton-85, a noble gas, causes an air-immersion dose only; and thus, soil and vegetation concentrations of ^{85}Kr are immaterial. The equation describing the relationship of $C_{sx,i}$ to $C_{ax,i}$, the air concentration at the residence location is:

$$C_{sx,i} = \frac{V_d\ C_{ax,i}}{1.0\ K_s} \times \frac{1}{\rho_b} \tag{3.36}$$

Equation 3.36 assumes that equilibrium exists between deposition and resuspension, and that the amount deposited becomes mixed to the depth of the shallow soils compartment, represented by the factor of 1.0 in the equation. Concentrations of ^3H and ^{14}C in vegetation were calculated according to Equations 3.31 and 3.32, replacing $A_{s,i}$ with $C_{sx,i}$ and $C_{a,i}$ with $C_{ax,i}$. That is:

$$C_{vx,i}^{inh} = B_{iv} \times \frac{C_{sx,i}}{V_s} \times \frac{1}{\rho_b} \tag{3.37}$$

and

$$C_{vx,i}^{ext} = \frac{V_d \times F_v}{\lambda_w} \times C_{ax,i} \tag{3.38}$$

where $C_{vx,i}^{int}$ and $C_{vx,i}^{ext}$ are the vegetation concentrations at the offsite location. The total vegetation concentration, $C_{vx,i}$, is the sum of $C_{vx,i}^{int}$ and $C_{vx,i}^{ext}$.

Concentrations of ^3H and ^{14}C in milk and beef from direct inhalation of volatile forms of these radionuclides was neglected. Livestock intake of these radionuclides was calculated for the non-volatile forms only.

The CEDE from inhalation of ^3H and ^{14}C was calculated from:

$$D_i^{inh} = C_{ax,i} \times DCF_i^{inh} \times 8400 \qquad (3.39)$$

where $C_{ax,i}$ is the CAP88-determined air concentration at the offsite location in Ci m^{-3}. The dose conversion factor for ^3H was corrected for dermal adsorption by multiplying by 1.5

assumed value of the resuspension rate, K_s, is 10^{-4} yr^{-1}. Maximum and 10,000-year air concentrations at the two locations are presented in Table E.5. Concentrations in soil ($C_{rs,i}$) and vegetation ($C_{v,i}$) at both residence locations were calculated

according to Equation 3.36, 3.37, and 3.38. Concentrations in beef and milk were calculated assuming cattle grazed over the Area 5 RWMS after loss of institutional control (Equations 3.33 and 3.34). Inhalation and ingestion doses were calculated according to Equation 3.39 and 3.40. External doses were calculated according to Equation 3.28, removing the 2000/8760 factor to allow for continuous exposure throughout the year. Results are presented in Section 4.1.

3.2.4 Summary of Pathway Conceptual Models

The pathway conceptual model estimates the TEDE to members of the general public based on release rates of radionuclides from the RWMS or concentrations in the near-field environment. In the transient occupancy scenario, the concentration of radionuclides in shallow soils was used to estimate the external dose and inhalation dose to a transient visitor to the site. In the open rangeland scenario, the radionuclide concentration of shallow soils and vegetation at the Area 5 RWMS was used to estimate the radionuclide intake of cattle grazing on the site. Concentrations in air, soil, and vegetation at Indian Springs and Cane Springs, two locations with sufficient water resources to assume full-time residence, are also evaluated based on release rates of volatile and non-volatile radionuclides. The results of these analyses are presented in Chapter 4. Parameters assumed for these calculations are summarized in Table 3.15.

Table 3.15. Parameters used in the release and pathways conceptual model to estimate environmental concentrations and TEDE.

Parameter Description	Pathway Assumed	Value Assumed	Source of Value Selected
B_{iv}, Plant-Soil Concentration Ratio (Ci g^{-1} dry plant: Ci g^{-1} dry soil)	Internal Contamination of Vegetation	Table E.1	see Table E.1
DCF_i^{ext}, External Effective Dose Equivalent Conversion Factor (mrem yr^{-1} per Ci m^{-3} soil)	Exposure to Contaminated Soil	Table E.3	Eckerman and Ryman, 1993
DCF_i^{ing}, Ingestion CEDE Conversion Factor (rem per μCi)	Exposure to Contaminated Vegetation, Beef or Milk	Table E.3	USDOE, 1988b
DCF_i^{inh}, Inhalation Dose Conversion Factor (rem per μCi)	Exposure to Contaminated Air	Table E.3	USDOE, 1988b

Table 3.15. continued.			
Parameter Description	**Pathway Assumed**	**Value Assumed**	**Source of Value Selected**
E_f, Enrichment Factor	Suspension of Contaminated Soil into Air	1	Layton et al. 1993
F_b, Fraction of a Cow's Daily Ingestion of Radionuclide i that is in Each kg of Beef (day kg^{-1})	Contamination of Beef	Table E.1	see Table E.1
F_m, Fraction of a Cow's Daily Ingestion of Radionuclide i that is in Each kg of Milk (day kg^{-1})	Contamination of Milk	Table E.1	see Table E.1
F_v, Foliar Interception Factor (m^2 g^{-1})	External Contamination of Vegetation	10^{-3}	Martin and Bloom, 1980
I_s, Soil Ingestion Rate for Cattle (kg day^{-1})	Contamination of Beef and Milk	0.5	Martin and Bloom, 1980 Smith, 1977
I_v, Native Forage Consumption Rate for Cattle, (kg dry day^{-1})	Contamination of Beef and Milk	8	Martin and Bloom, 1980
K_{b1}, Fractional Transfer Rate from Waste to Shallow Soils by Burrowing Animals (yr^{-1})	Contamination of Shallow Soils	1.3 x 10^{-7}	see Section 3.2.2
K_{b2}, Fractional Transfer Rate from Waste to Subsurface Soils by Burrowing Animals (yr^{-1})	Contamination of Subsurface Soils	1.8 x 10^{-7}	see Section 3.2.2
$K_{r1,i}$, Root Uptake Rate from Waste to Shallow Soils (yr^{-1})	Contamination of Shallow Soils	Table E.2	see Section 3.2.2
$K_{r2,i}$, Root Uptake Rate from Waste to Subsurface Soils (yr^{-1})	Contamination of Subsurface Soils	Table E.2	see Section 3.2.2
$K_{r3,i}$, Root Uptake Rate from Subsurface Soils to Shallow Soils (yr^{-1})	Contamination of Shallow Soils	Table E.2	see Section 3.2.2
K_s, Soil Resuspension Rate (yr^{-1})	Source Term for Atmospheric Transport Offsite	10^{-4}	see Section 3.2.2
M_s, Mass Loading Factor (g m^{-3})	Contamination of Air Above Facility	10^{-4}	USEPA, 1990
U_b, Average Intake Rate of Beef (kg wet yr^{-1})	Exposure to Contaminated Beef	30	Rupp, 1990
U_m, Average Intake Rate of Milk (kg wet yr^{-1})	Exposure to Contaminated Milk	220	Rupp, 1990
U_s, Inadvertent Intake Rate of Soil (g yr^{-1})	Exposure (internal) to Contaminated Soil	40	USEPA 1989
U_v, Average Intake Rate of Vegetables and Fruit (g dry yr^{-1})	Exposure to Contaminated Vegetation	32000	Rupp, 1990

Table 3.15. continued.			
Parameter Description	**Pathway Assumed**	**Value Assumed**	**Source of Value Selected**
V_d, Deposition Velocity (m yr^{-1})	External Contamination of Vegetation and Offsite Soil	3.3×10^4	Baes et al. 1984, USEPA, 1992
V_s, Volume of the Shallow Soils Compartment (m^3)	Contamination of Shallow Soils	7.5×10^4	see Section 2.9
$\lambda_{r,i}$, Radioactive Decay Constant, yr^{-1}	Contamination of Air and Soils	Table E.3	Kocher, 1981
λ_w, Weathering Constant for External Contamination of Vegetation, yr^{-1}	External Contamination of Vegetation	18	USNRC, 1977
ρ_b, Dry Bulk Density of Soil (g m^{-3})	Contamination of Shallow Soils	1.6×10^6	REECo, 1993c

3.3 INTRUDER CONCEPTUAL MODELS AND ASSUMPTIONS

In Section 3.1.3, the intruder scenarios evaluated in the performance assessment were described. The scenarios selected are based on scenarios previously developed (USNRC, 1981; Kennedy and Peloquin, 1988). This assessment does not consider intruder scenarios to be reasonable predictions of future events. They are arbitrary hypothetical events. Intruder scenarios have been analyzed to set waste concentration limits. It is the policy of the USDOE to ensure that no legacy requiring remedial action remains after operations have been terminated (USDOE, 1988a). Analysis of intruder scenarios is a method to ensure that the site is preserved for very restrictive future uses, thereby ensuring that the site is not a legacy. This is accomplished by determining the maximum waste concentration that meets the performance objective. This section describes the conceptual models and assumptions used to analyze the intruder scenarios. The conceptual models were implemented with the RESRAD computer code (Yu et al. 1993). The RESRAD results presented are all for zero elapsed time, thereby eliminating the time dependant processes (erosion, leaching, and radioactive decay) incorporated in the RESRAD code. Erosion and leaching of the contaminated zone are not believed to be important processes at the NTS over the short duration of an intruder scenario. Radioactive decay of the source term was performed with the RadDecay computer code (Negin and Worku, 1991).

3.3.1 Acute Intruder Scenarios

Three acute intruder scenarios were considered, the discovery scenario, intruder-construction scenario, and intruder-drilling scenario. Intrusion was assumed to be possible from the end of the 100-year institutional control period to the end of the 10,000-year compliance interval. Two of the scenarios, the discovery and the intruder-construction scenario, were not analyzed because the expected doses are bounded by chronic intruder scenarios. The discovery scenario and intruder-construction scenario are very similar except that the discovery scenario can occur earlier, before waste forms have decomposed. Since no credit for waste form is taken in this assessment and all waste forms are assumed to have decayed to a soil-like material by the end of the institutional control period, the discovery and construction scenarios are assumed equivalent.

The intruder-construction scenario describes the exposure of an intruder building a residence over the site. It is an acute scenario which precedes the chronic intruder-agriculture scenario. Based on previously described scenarios (USNRC, 1981), the intruder is assumed to excavate 600 m^3 from a 10 by 20 m foundation that is 3-m deep. Since the assumed cap thickness is 2.4 m, 120 m^3 of waste is excavated and mixed with 480 m^3 of clean soil. In the ensuing intruder-agriculture scenario, the intruder is assumed to spread the contaminated soil over a 2,500 m^2 area. The thickness of the contaminated area is then 600 m^3/ 2,500 m^2 or 0.24 m. Since 0.24 m is greater than the depth of mixing by most agricultural implements, the soil is not diluted any further. Therefore, the soil concentrations in the intruder-construction and intruder-agriculture scenario are the same. There are other differences between the two scenarios. Inhalation exposure in the intruder-construction scenario is greater because a higher dust loading of 5.65×10^{-4} g m^{-3} is assumed versus 1.54×10^{-4} g m^{-3} assumed for the intruder-agriculture scenario. However, overall exposure in the intruder-agriculture scenario is greater because the duration of exposure is greater, 6,132 hours versus 500 hours, and there are no ingestion pathways in the intruder-construction scenario. The acute scenario also has a performance objective that is five times greater than for the chronic scenario. The intruder-agriculture scenario is expected to yield doses bounding the intruder-construction scenario because the soil concentrations are the same and the time of exposure is ten times greater, the dose limit is one-fifth and additional pathways are included. Therefore, the intruder-construction scenario and discovery scenario were not considered.

3.3.1.1 Conceptual Models and Assumptions for the Acute Drilling Scenario

The drilling intruder scenario is a short-term, or acute scenario involving exposure to drill cuttings from a borehole penetrating a trench or pit. Again, since no credit is taken for the waste form integrity, this scenario is assumed to be possible at any time after the 100-year institutional control period. The site inventory is assumed to remain totally isolated until the time of intrusion. The models for radionuclide release from the undisturbed site, described in Section 3.2.2, predict that less than 5 percent of the inventory of the most mobile particulate radionuclides will be released from the facility in 10,000 years. Therefore, it is reasonable and conservative to assume that radioactive decay is the only process changing the source term prior to intrusion.

The drillers are assumed to be exposed to contaminated cuttings while drilling a 0.3 m diameter borehole to the uppermost aquifer. The time required to complete the drilling is assumed to be 100 hours. During the event, the drillers are assumed to be exposed by external irradiation, inhalation, and inadvertent ingestion of soil. The drillers are assumed to be in the center of a 1,000 m^2 area contaminated with cuttings for the 100-hour exposure period. Drill cuttings are usually held in a mud pit adjacent to the drill rig. The drillers were assumed to be in the mud pit to simplify the geometry of external irradiation. This is a conservative assumption made to simplify the analysis. The activity concentration of radionuclides in the cuttings is:

$$C_{s,i} = 1 \times 10^{12} \times C_{w,i} \times \frac{t_w f_d}{D_b \rho} \tag{3.42}$$

where:

$C_{s,i}$	=	soil activity concentration of radionuclide i, pCi g^{-1},
$C_{w,i}$	=	waste activity concentration of radionuclide i at the time of intrusion, Ci m^{-3},
t_w	=	thickness of the waste zone, m,
f_d	=	facility design factor, dimensionless,
D_b	=	total depth of the borehole, m, and
ρ	=	bulk density of the alluvium, g m^{-3}.

The waste activity concentrations at the time of intrusion were determined using RadDecay (Negin and Worku, 1991). The facility design factor is a dilution factor that accounts for clean soil that fills void spaces between waste packages. The design factor was assumed to be 0.75. The depth of the borehole was assumed to be 235 m and the bulk density was assumed to be 1.6×10^6 g m^{-3}. The waste cell thicknesses were 4.9 m for the shallow land burial trenches, 6.2 m for the upper cell of Pit 6, and 3.6 m for the lower cell. The volume of soil excavated, 17 m^3, when spread over a 1,000 m^2 area, creates a final contaminated zone approximately 0.02-m thick.

The CEDE to the drillers from the inadvertent ingestion of soil is given by:

$$D_{soil,i} = C_{s,i} \times DCF_{ing} \times FSI \times FA \times FCD_s \times FO_s \qquad (3.43)$$

where:

$D_{soil,\,i}$ = CEDE from ingestion of radionuclide i in soil, mrem yr^{-1},
DCF_{ing} = ingestion CEDE conversion factor, mrem pCi^{-1},
FSI = annual intake of soil, g yr^{-1},
FA = area factor, dimensionless,
FCD_s = soil ingestion cover and depth factor, dimensionless, and
FO_s = soil ingestion occupancy factor, dimensionless.

The dose conversion factors used are the default values in RESRAD. These are the most conservative values in USDOE (1988b, 1988c). This approach is reasonable, since no information on chemical or physical form of the waste constituents is available. The annual soil ingestion rate was assumed to be 40 g yr^{-1}. The area factor for a 1,000 m^2 area was assumed to be 1.0. The cover and depth factor was assumed also to be 1.0. The soil ingestion occupancy factor is the fraction of the time in a year spent onsite or 0.011 for 100 hours.

The CEDE from inhalation of suspended cuttings was calculated from:

$$D_{inh,i} = C_{s,i} \times DCF_{inh} \times ASR \times FA_{inh} \times FCD_{inh} \times FO_{inh} \times FI \qquad (3.44)$$

where:

$D_{inh,\,i}$ = CEDE from inhalation of radionuclide i, mrem yr^{-1},
DCF_{inh} = inhalation CEDE conversion factor, mrem pCi^{-1},
ASR = soil mass loading in air, g m^{-3},
FA_{inh} = area factor for inhalation pathway, dimensionless,
FCD_{inh} = inhalation cover and depth factor, dimensionless,
FO_{inh} = occupancy factor for inhalation pathway, dimensionless, and
FI = annual intake of air, m^3 yr^{-1}.

The soil mass loading was assumed to be 1.54×10^{-4} g m^{-3} based on the assumption that the drill cuttings would be wet and not readily resuspended. The cover and depth factor and occupancy factor were the same as in the soil ingestion pathway. The annual intake of air was assume to be 8,400 m^{3} yr^{-1}. The cover and depth factor was calculated as:

$$FA_{inh} = \frac{\sqrt{A}}{\sqrt{A} + DL} \tag{3.45}$$

where:

A	=	area of contaminated zone, m^2
DL	=	dilution length, m.

The area of the contaminated zone was 1,000 m^2 and the assumed dilution length is 3 m.

The dose from inhalation of ^{3}H was calculated assuming HTO was the only form present. The CEDE from inhalation and dermal absorption of HTO was calculated from:

$$D_{inh,H\text{-}3} = 1.5 \times DCF_{inh} \times FO_{inh} \times FI \times C_{a,H\text{-}3} \tag{3.46}$$

where:

$D_{inh,\,H\text{-}3}$	=	CEDE from inhalation and absorption of HTO, mrem yr^{-1}, and
$C_{a,\,H\text{-}3}$	=	activity concentration of HTO in air, pCi m^{-3}.

The concentration of HTO in air is calculated assuming that all of the HTO is in the soil pore water. The flux from the surface is the product of the soil pore water ^{3}H concentration and annual evapotranspiration. This flux is assumed to be mixed into a 2-m mixing zone. The concentration of HTO in air is given by:

$$C_{a,H\text{-}3} = \frac{3.17 \times 10^{-8} \times 0.5 \times \dfrac{\rho\, C_s}{\theta_v} \times E_t \times \sqrt{A}}{H_{mix} \times U} \tag{3.47}$$

where:

θ_v	=	volumetric water content, dimensionless,
E_t	=	evapotranspiration rate, m yr^{-1},
H_{mix}	=	height of atmospheric mixing zone, m, and
U	=	mean wind speed, m s^{-1}.

The volumetric water content of the cuttings was assumed to be the same as the near surface alluvium, 0.086. The evapotranspiration factor is the annual quantity of water evaporated from the surface, which was assumed to be equal to the annual rainfall of about 0.1 m yr^{-1}. The mixing height and mean wind speed assumed were 2 m and 2 m s^{-1}, respectively.

The dose from inhalation of ^{14}C is calculated in a similar fashion. All airborne ^{14}C is assumed to be $^{14}CO_2$. The CEDE from inhalation of $^{14}CO_2$ is calculated as:

$$D_{inh,C\text{-}14} = DCF_{inh} \times FO_{inh} \times FI \times C_{a,C\text{-}14} \tag{3.48}$$

where:

$D_{inh,\,C\text{-}14}$ = CEDE from inhalation of $^{14}CO_2$, mrem yr^{-1}, and
$C_{a,\,C\text{-}14}$ = activity concentration of $^{14}CO_2$ in air, pCi m^{-3}.

The concentration of $^{14}CO_2$ in air is estimated from:

$$C_{a,C\text{-}14} = \frac{3.17 \times 10^{-8} \times 0.5 \times EVSN \times \sqrt{A}}{H_{mix} \times U} \tag{3.49}$$

where:

EVSN = the $^{14}CO_2$ evasion rate, pCi m^{-2} yr^{-1}.

The same values for the area, mixing height, and wind speed were used for ^3H and were used for $^{14}CO_2$.

The carbon evasion rate is estimated from:

$$EVSN = 1\times10^{6} \times C_{s,C\text{-}14} \times E \times \rho \times d_{ref} \tag{3.50}$$

where:

E = carbon evasion rate constant, yr^{-1}, and
d_{ref} = reference soil depth, m.

The carbon evasion rate constant was assumed to be 22 yr^{-1} which is a RESRAD default

The effective dose equivalent from external irradiation was calculated from:

$$D_{ext,i} = C_{s,i} \times DCF_{ext} \times \rho \times FO_{ext} \times FS \times FA \times FD \times FC \qquad (3.51)$$

where:

$D_{ext,i}$ = effective dose equivalent from external exposure, mrem yr^{-1},
DCF_{ext} = external dose conversion factor, mrem yr^{-1} per pCi m^{-3},
FS = shape factor, dimensionless,
FD = depth factor, dimensionless,
FC = cover factor, dimensionless, and
FO_{ext} = occupancy factor for external irradiation, dimensionless.

The shape factor, area factor, and cover factor were assumed to be 1.0. The depth factor corrects the external dose conversion factor for an infinitely deep contaminated zone to a value appropriate for the actual depth of the contaminated zone. The depth factor is determined within RESRAD for each radionuclide by interpolation between tabulated values (Yu et al. 1993). The occupancy factor for external irradiation is the fraction of time spent at the site annually or 0.011. Parameters used in the acute drilling scenario are summarized in Table 3.16.

Table 3.16. Summary of parameters used in the drilling intruder scenario.

Parameter	Acute Intruder Scenarios
	Drilling
Area of Contaminated Zone (m^2)	1,000
Thickness of Contaminated Zone (m)	0.016
Bulk Density of Contaminated Zone (g m^{-3})	1.6×10^6
Occupancy Factors Soil Ingestion Inhalation External	 0.011 0.011 0.011
Mass Loading (g m^{-3})	1.54×10^{-4}
Soil Ingestion Rate (g yr^{-1})	40
Annual Intake of Air (m^3 yr^{-1})	8,400
Annual Evapotranspiration Factor, E_t (m yr^{-1})	0.099
Atmospheric Mixing Height, H_{mix} (m)	2

- external irradiation from radionuclides in surface soil,

- inhalation of particulate radionuclides resuspended from surface soils and inhalation of gaseous radionuclides release from surface soil,

- inhalation of gaseous radionuclides released from buried waste,

- ingestion of contaminated soil,

- ingestion of contaminated beef and dairy products produced at the site, and

- ingestion of contaminated fruits and vegetables produced at the site (Figure 3.8).

The intruder is assumed to construct a 200-m^2 house with a 2.5-m deep basement. The excavation is assumed to be 3-m deep. Although basements are not commonly constructed in southern Nevada, there are no physical obstacles that preclude excavation at the site. In addition, there are other alternative types of excavations that could occur during construction [illegible]

Suspended

The facility design factor was set equal to 0.75, and the bulk density of the contaminated zone was assumed to be 1.6×10^6 g m^{-3}.

The CEDE from soil ingestion was calculated using Equation 3.43. The occupancy factor for the chronic exposure scenario is different than for the acute scenario. The intruder is assumed to be indoors 50 percent of the time, outdoors 20 percent of the time, and offsite for 30 percent of the time, resulting in an soil ingestion occupancy factor of 0.7.

The CEDE from inhalation of resuspended particulate radionuclides from the contaminated zone was calculated using Equations 3.44 and 3.45. The inhalation occupancy factor assumes that indoor dust loading is 40 percent of outdoor levels. This yields an inhalation occupancy factor of 0.4.

The CEDE from inhalation of volatile HTO and $^{14}CO_2$ released from the surface contaminated zone was calculated as in Equations 3.46 through 3.50. All parameters were the same, except the soil reference depth was set to be equal to the depth of the contaminated zone, 0.24 m. The CEDE from inhalation of ^{222}Rn and its short-term progeny released from the surface contaminated zone was calculated using RESRAD models.

Calculation of doses from HTO, $^{14}CO_2$, and ^{85}Kr released from the waste zone was performed independently from RESRAD. This calculation was performed for the 100-year time interval only, since it assumed that the inventory would be completely released by 10,000 years. The inhalation CEDE from outdoor exposure was calculated using Equations 3.26 and 3.30. However, in Equation 3.30, the time of exposure was the time spent outdoors, 1,752 hours, rather than 1,920 hours. The RESRAD models were used to estimate the CEDE from ^{222}Rn and its short-term progeny released from the waste. These models include estimates for doses received indoors and outdoors.

The CEDE from inhalation of HTO, ^{14}C, and ^{85}Kr while indoors was calculated separately from RESRAD. The indoor HTO, ^{14}C, and ^{85}Kr concentration was calculated by converting the release rate in Section 3.2.2.1 to a flux and assuming a steady state concentration in the house. Neglecting radioactive decay, the steady state gas concentration in the residence, $C_{gas\ i,\ Ind}$, is then:

$$C_{gas\,i,Ind} = \frac{J_i A_f}{k V} \qquad (3.53)$$

where:

J_i	=	flux of radionuclide i into residence, pCi m^{-2} yr^{-1};
A_f	=	area of foundation below the ground surface, m^2,
k	=	ventilation exchange rate, yr^{-1}, and
V	=	internal volume of the residence, m^3.

The estimated ^{14}C release rate from the site of 4.12 Ci yr^{-1} gives a flux of 5.5×10^7 pCi m^{-2} yr^{-1}. The ^{85}Kr flux was 3.5×10^5 pCi m^{-2} yr^{-1}. These flux rates assume that the entire site inventory is released in a single year. The HTO release rate of 200 Ci yr^{-1} gives a flux rate of 2.7×10^9 pCi m^{-2} yr^{-1}. The total area of the foundation, including the walls, is 350 m^2 and the volume of the residence is 1,000 m^3. The assumed ventilation rate was 0.5 hr^{-1}. The CEDE from HTO and $^{14}CO_2$ is calculated as in Equation 3.30 with the volume of air inhaled changed from 1920 m^3 to 1680 m^3 to account for the different exposure times. The ^{85}Kr dose was calculated using an effective dose equivalent conversion factor for immersion.

The dose received from external irradiation from the contaminated zone was calculated using Equation 3.51. The external exposure occupancy factor in this case includes a shielding factor for the residence of 0.7.

Ingestion doses were calculated for ingestion of contaminated fruits, vegetables, beef, and dairy products. The annual quantities of food ingested were the same as used in the pathway scenarios. The fraction of the diet obtained onsite was assumed to be 0.25. RESRAD includes formulae to estimate the amount of food that can be grown in the contaminated zone (Yu et al. 1993). For a 2,500 m^2 area, RESRAD estimates that 50 percent of a resident's vegetables and 12.5 percent of beef and dairy products can be produced onsite. The vegetable fraction was adjusted downward to 25 percent given the difficulties of gardening in southern Nevada, and the animal product fraction was adjusted upward to 25 percent, because livestock production is more likely. Comparison of these estimates with agricultural statistics for Nevada (USDOE, 1987) indicate that they are physically possible. The

FD	=	fraction of diet derived from contaminated zone, dimensionless,
DF_{veg}	=	annual plant intake, g yr^{-1},
FCD_{veg}	=	cover and depth factor, dimensionless,
B_{iv}	=	plant-soil concentration ratio, pCi g^{-1} plant per pCi g^{-1} soil,
FA_{inh}	=	area factor for resuspension of soil particulates, dimensionless,
ASR	=	mass loading factor, g m^{-3}, and
FAR	=	foliar deposition factor, m^3 g.

The assumed annual plant intake is 32 kg on a dry mass basis and 160 kg on a wet mass basis. The plant-soil concentration ratios, B_{iv}, are the same as described in the pathway scenarios (Table E.1). These are dry mass factors requiring that dry mass annual intake factors be used for plant intake by the resident and fodder intake by livestock. Calculations for ^3H and ^{14}C were performed with wet mass transfer factors and intake rates. For root

uptake, the cover and depth factor, FCD_{inh}, is the contaminated zone thickness divided by the rooting depth (0.9 m) or 0.27. The area factor is calculated from Equation 3.45. The foliar deposition factor, FAR, is calculated from:

$$FAR = 3.16 \times 10^4 \frac{(V_d f_r T)(1 - e^{(-\lambda_w t_e)})}{Y \lambda_w} \tag{3.55}$$

where:

V_d	=	deposition velocity, m s^{-1},
f_r	=	fraction of deposited nuclides retained, dimensionless,
T	=	foliage to food transfer coefficient, dimensionless,
λ_w	=	weathering constant, yr^{-1},
t_e	=	time of exposure, yr, and
Y	=	crop yield, kg m^{-2}.

The parameters in the foliar deposition equation can not be changed by the user. The FAR of ^{14}C ... is calculated assuming that the specific activity remains constant during

DF_f	=	intake of fodder by livestock, g day^{-1}, and
DF_s	=	intake of soil by livestock, g day^{-1}.

The fodder-to-meat transfer coefficients are the same as were used in the pathway scenarios (see E.1). The intake rates assumed are specified in Table 3.16.

Analysis of the intruder-agriculture scenario was performed for the shallow land burial inventory at 100 years, 10,000 years, and at the time of maximum activity for radionuclides with maximums beyond 10,000 years. This scenario is not required for Pit 6 because the waste activity concentration in the upper cell is the same as that for the shallow land burial inventory, and the lower cell is too deep for this scenario to be credible.

3.3.2.2 Conceptual Model and Assumptions for the Post-Drilling Scenario

In the post-drilling scenario, an intruder is assumed to construct a residence on a site contaminated with drill cuttings from a waste disposal cell. The intruder is assumed to raise livestock and cultivate fruit, vegetables, and fodder as in the intruder-agriculture scenario. The exposure pathways are identical to those included in the intruder-agriculture scenario (Figure 3.9). Overall, the post-drilling scenario is the same as the intruder-agriculture scenario with three exceptions. First, the volume of waste exhumed is less; and consequently, the thickness and the activity concentration of the contaminated zone is less. Second, the inventory of waste that can be exhumed is expanded because the borehole passes through the entire trench to the uppermost aquifer. This second distinction requires that the special case thorium waste, disposed of in the lower cell of Pit 6, be analyzed in this scenario. Third, the post-drilling intrusion scenario does not include the excavation of a basement in the waste site.

[illegible]

common agricultural implements. The activity concentration of radionuclides in the contaminated zone is calculated as:

$$C_{s,i} = 1\times10^{12} \times C_{w,i} \times \frac{\pi r^2 t_w f_d}{A_c D_c \rho} \tag{3.58}$$

where:

$C_{s,i}$	=	soil activity concentration of radionuclide i, pCi g^{-1},
r	=	radius of the borehole, m,
t_w	=	thickness of the waste zone, m,
f_d	=	facility design factor, dimensionless,
A_c	=	area of the contaminated zone, m^2,
D_c	=	final depth of the contaminated zone, m, and
ρ	=	bulk density of the alluvium, g m^{-3}.

The pathway models described in the previous sections were used to estimated the TEDE to the post-drilling intruder. Again, the only differences between features included in the two scenarios are the inventory available, the activity concentration of the contaminated zone, the thickness of the contaminated zone, and the presence of a basement. The parameters used are the same except those that are tied to the contaminated zone thickness. These parameters are the soil reference depth in the carbon evasion model (Equation 3.50), the depth factor in the external exposure model (Equation 3.51), and the cover and depth factor in the plant ingestion model (Equation 3.54). Parameters used in both chronic scenarios are summarized in Table 3.17.

Table 3.17. Summary of parameters used in the intruder-agriculture and post-drilling intruder scenarios.

Parameter	Chronic Intruder Scenarios	
	Intruder-Agriculture	Post-Drilling
Area of Contaminated Zone (m^2)	2,500	2,500
Thickness of Contaminated Zone (m)	0.24	0.15
Bulk Density of Contaminated Zone (g m^{-3})	1.6×10^6	1.6×10^6

Table 3.17. continued.		
Parameter	**Chronic Intruder Scenarios**	
	Intruder-Agriculture	**Post-Drilling**
Occupancy Factor		
Soil Ingestion	0.7	0.7
Inhalation	0.4	0.4
External	0.55	0.55
Mass Loading (g m^{-3})	1.54×10^{-4}	1.54×10^{-4}
Soil Ingestion Rate (g yr^{-1})	40	40
Annual Intake of Air (m^{-3} yr^{-1})	8,400	8,400
Annual Intake of Fruit and Vegetable (kg yr^{-1})	160 (wet), 32 (dry)	160 (wet), 32 (dry)
Annual Intake of Meat Products (kg yr^{-1})	30	30

ZERO (Kirchner, 1990) is an integrated set of software tools which simplifies the process of writing simulation models. One of the tools is an interactive code generator which simplifies the construction of computer models. The linear differential equations are written in TIME-ZERO, which then automatically produces the FORTRAN source code.

The differential equations describing the release of non-volatile radionuclides (Equations 3.23 through 3.25) were solved using the TIME-ZERO computer code (Kirchner, 1990). The

solutions to the equations describing the plant uptake and burrowing animal system were developed and used for verification of the results. However, the TIME-ZERO model was needed for solution of radionuclide decay chains because analytical solutions are not easily obtainable. Two models were developed in TIME-ZERO, a model for handling single radionuclides referred to as MODELNTS and a model to handle decay chains with up to

The analytical solution giving the activity in the subsurface soil compartment was:

$$A_{u,i}\ (t) = A_{w,i}\ (t=0) \times (K_{b2} + K_{r2,i}) \times \frac{e^{-(K_{eff,i}\ t)} - e^{-((\lambda_{r,i} + K_{r3,i})\ t)}}{(\lambda_{r,i} + K_{r3,i} - K_{eff,i})} \tag{3.60}$$

where:

$A_{u,i}$	=	activity of radionuclide i in subsurface soil compartment, Ci, and
$K_{r3,i}$	=	rate constant for radionuclide i transport to surface soil from plant roots in subsurface soil, yr^{-1}.

The analytical solution for the activity in the surface soil compartment was:

$$\begin{aligned} A_s\ (t) &= (K_{b1}+k_{r1}) \times A_w(t=0) \times \frac{e^{-(k_{eff}\ t)} - e^{-((\lambda_r + k_s)\ t)}}{((\lambda_r + k_s) - K_{eff})} \\ &+ \frac{(K_{b2} + K_{r2}) \times A_w(t=0) \times K_{r3}}{((\lambda_r + K_{r3}) - k_{eff})((\lambda_r + K_s) - K_{eff})} \times e^{-(k_{eff}\ t)} \\ &+ \frac{(K_{b2} + K_{r2}) \times A_w(t=0) \times K_{r3}}{(K_{eff} - (\lambda_r + K_{r3}))((\lambda_r + K_s) - (\lambda_r + K_{r3}))} \times e^{-((\lambda_r + K_{r3})\ t)} \\ &+ \frac{(K_{b2} + K_{r2}) \times A_w(t=0) \times K_{r3}}{(k_{eff} - (\lambda_r + K_s))((\lambda_r + K_{r3}) - (\lambda_r + K_s))} \times e^{-((\lambda_r + K_s)\ t)} \end{aligned} \tag{3.61}$$

where:

A_s	=	activity in surface soil compartment, Ci, and
K_s	=	rate constant for resuspension, yr^{-1}.

In addition, mass balance checks were made for each simulation based upon the conservation of atoms. This was accomplished by converting the activity in each compartment at any time t to the number of atoms according to:

$$N_j = \frac{C_j(i) \times CF}{\lambda_r(i)} \tag{3.62}$$

where:

$N_j(i)$ = number of atoms of radionuclide i in compartment j,
$C_j(i)$ = activity of radionuclide i in compartment j, Ci,
$\lambda_{r,i}(i)$ = decay rate constant of radionuclide i , yr^{-1}, and
CF = conversion factor, disintegrations yr^{-1} per Ci (1.1668 x 10^{18}).

An air compartment was added to the TIME-ZERO models to ensure that atoms were not lost from the system. The air compartment was a sink for atoms being transferred from the surface soil compartment to the air by the resuspension rate constant.

The percent difference in the initial number of atoms and the number of atoms at any time t was then calculated as:

$$PD = \frac{(N_t - N_i)}{N_i} \times 100 \tag{3.63}$$

where:

PD = percent difference in the number of atoms,
N_i = initial number of atoms,
N_t = number of atoms at time t during the simulation, and
100 = conversion factor to percent.

The analytical solutions and conservation of atoms were sufficient checks to ensure that the numerical solution was accurate for single radionuclides. However, radionuclide chains were more difficult to assess. Radionuclide chain solutions were checked for accuracy by three methods: (1) the first radionuclide in the chain was checked against the analytical solution to ensure that the root uptake and burrowing animal models were accurate, (2) the overall conservation of atoms was tracked to ensure that atoms were neither lost nor gained in the system, and (3) the ingrowth of a given progeny was verified by summing all of the model compartments (i.e., waste compartment, subsurface soil compartment, surface soil compartment, and the air compartment) and comparing the number of progeny atoms from TIME-ZERO to the result from the Bateman ingrowth equations. The solution of radionuclide chains in a numerical model requires simplification of the chains. The simplification is required to prevent the development of a stiff differential equation. The simplification involves modeling only those members of the decay chain with half-lives equal to or greater than 1 year. Assumptions for the remaining radionuclides with half-lives less than 1 year can be made assuming equilibrium and factoring in the branching fractions.

All of the model runs were found to have less than 1 percent error in the mass balance of atoms. This was considered acceptable for a numerical solution to the linear differential equations.

3.4.2 The CASCADR9 Computer Code

The CASCADR9 computer code was used to estimate radon fluxes from waste disposal cells. CASCADR9 was developed to model the transport of radon in porous media. It considers the effects of molecular diffusion, advection, and radioactive decay of radon in the air-filled includes an additional transport process (advection) and neglects the effects of water-filled pores. The observation that the two methods give equivalent results for the shallow land burial problem suggest that the effects of advection and water-filled pore spaces are negligible for this case. The second test evaluated was the four layer problem describing Pit 6. Again, each model was run with identical parameters, and the differences noted. The K factors (flux per activity concentration, m s^{-1}) for the upper cells are nearly identical (Table 3.18). However, for the lower cell test case, the CASCADR9 K factor is slightly greater than the Regulatory Guide 3.64 factor. The higher K factor for CASCADR9 translates into higher fluxes and is therefore conservative.

Table 3.18. Results of benchmark tests between CASCADR9 and USNRC Regulatory Guide 3.64.

Test Cases	K Factors	
	CASCADR9	USNRC Reg. Guide 3.64
Shallow Land Burial (K_{SLB})	5.6×10^{-8} m s^{-1}	5.5×10^{-8} m s^{-1}
Pit 6 Upper Cell (K_{P6U})	5.3×10^{-8} m s^{-1}	5.5×10^{-8} m s^{-1}
Pit 6 Lower Cell (K_{P6L})	3.3×10^{-11} m s^{-1}	2.7×10^{-11} m s^{-1}

3.4.3 The RESRAD Computer Code

The RESRAD computer code (Version 5.43) was used in the intruder scenario analyses to convert the soil concentrations in the contaminated zone into dose equivalents. The RESRAD code is a USDOE-sanctioned code designed for the development of site-specific clean-up criteria. The RESRAD code was selected because it was developed for USDOE assessments and has a documented quality assurance history. It affords a convenient method to perform pathway analysis on a large number of radionuclides.

The RESRAD code has the capability to predict the concentration of radionuclides over time by including radioactive decay and redistribution effects such as erosion and leaching. The results used in this assessment are the results provided for the case where the elapsed time is zero. This eliminates all time dependant effects from the model. The dose equivalents are then linearly proportional to the soil concentration as described in Section 3.3.

A verification of the RESRAD pathway analyses was performed by spreadsheet calculations using the parameters and equations described in Section 3.3. The difference between the verification results and the RESRAD results were generally less than 1 percent. The only exception was the doses from ^{3}H and ^{14}C in the ingestion pathways. In these cases, results

3.5 QUALITY ASSURANCE

Preparation of the performance assessment has been subject to the quality assurance requirements described in the REECo Quality Management Plan (QMP). The QMP implements the requirements in USDOE Order 5700.6C.

The QMP provides broad direction for planning and accomplishment of activities affecting quality under suitably controlled conditions, including training and indoctrination of personnel, documentation of conditions found during surveillance and audits, testing, special processes, and use of computer codes and equipment to ensure the accomplishment of the performance objectives.

3.5.1 Site Characterization and Monitoring Quality Assurance

The Environmental Restoration & Technology Development Department, Special Projects Section (ER&TDD-SPS) Procedure ER&TDD-SP.01.28, describes the key elements of the Quality Assurance Plan (QAP) supporting ER&TDD-SPS Site Characterization and Monitoring Tasks for the NTS. ER&TDD-SPS is the organization responsible for the maintenance of this procedure.

Procedure ER&TDD-SP.01.28 provides documentation and planning for a variety of activities such as design control, organizational structure and function, QAP, procurement document control, document control, control of purchased items and services, identification and control of processes, inspection, control of measuring and test equipment, handling, storage, and shipment, corrective action, quality assurance records, training, and regulatory drivers related to site characterization and monitoring. This procedure controls specific site characterization activities conducted by REECo. These activities include surface and borehole geophysical surveys, soil gas sampling, surface core sampling, drilling, borehole core sampling, well and instrument installation, in situ vadose zone monitoring, aquifer testing, groundwater sampling, and computer modeling.

3.5.2 Software Quality Assurance

Modeling tasks supporting the performance assessment were performed by personnel at REECo and Oak Ridge National Laboratory/Grand Junction. Each organization was responsible for the development and maintenance of software quality assurance procedures.

Each investigator performing modeling analyses followed written quality assurance procedures implementing the requirements of NQA-1 (ASME, 1989) and USDOE/LLW-102 (Seitz et al. 1990).

Software was selected based on its applicability to the conceptual model of the system and level of documentation. Preference was given to software developed and sanctioned by U.S. government agencies for use in radiological assessments or to codes with documented histories of quality assurance testing and verification. Two codes were developed by REECo, CASCADR9, and BAT6CHN. These codes were developed under REECo Procedure WOD-B09, "Mathematical Modeling and Model Building." Software analysis, the process of evaluating software quality by conducting analyses of variable usage, complexity analysis or coverage analysis, was not performed for commercial or U.S. government-sanctioned software.

Each investigator performing modeling analyses was responsible for maintaining control of

4.0 RESULTS OF ANALYSIS

This chapter describes the results of the performance assessment, discusses the parameter sensitivity and the uncertainty of the performance assessment results. The performance assessment has considered two classes of scenarios. The first class of scenarios, the release and pathway scenarios described in Sections 3.1.1 and 3.1.2, represents a reasonable, yet conservative, estimate of the performance of the undisturbed site. These scenarios were analyzed to estimate the TEDE to members of the general public. The relevant performance objectives for these analyses are 25 mrem yr^{-1} for all pathways, 10 mrem yr^{-1} from atmospheric pathways, an annual average radon flux rate less than 20 pCi m^{-2} s^{-1}, and a requirement to protect groundwater resources.

The second class of scenarios analyzed, described in Section 3.1.3, are the intruder scenarios. These assume future residents at the site have inadvertently exhumed buried waste and are exposed to the contamination while residing at the site. Intruder scenario analyses are performed to set concentration limits for wastes that can be disposed of in the facility.

yr^{-1} at the time their concentrations reach a maximum in the shallow soil compartment. Nuclides not meeting this criterion were not analyzed. Tritium and ^{14}C were evaluated as if the inventory was both gaseous and non-volatile. This causes a conservative double counting of ^{3}H and ^{14}C that was considered acceptable given the low doses expected. Nine non-volatile radionuclides were found to meet the screening criterion. All reach their peak concentration after the 10,000-year compliance interval. Therefore, the maximum dose in [illegible] of $^{238}U+D$. Since estimated doses will scale linearly with time of occupancy, it is possible to estimate the dose per hour spent at the site. The model predicts that individuals visiting the site 10,000 years after closure will receive an external effective dose equivalent and a CEDE summing to approximately 0.3 μrem for each hour spent at the site. The maximum TEDE is expected to occur about 700,000 years after closure and is estimated to be about 9 mrem yr^{-1}. The maximum dose occurs when the progeny of ^{238}U, that is ^{230}Th, ^{226}Ra, and ^{210}Pb, reach their maximum total concentration in the surface soil compartment. Approximately 98 percent of the dose at 700,000 years is from external irradiation from $^{226}Ra+D$.

The estimates above were made assuming a 2.4 m depth of burial. As sediments should accumulate over the site in the intervening 700,000 years, these calculations are highly conservative. The additional depth of burial will significantly reduce the dose by reducing or eliminating upward release pathways.

Gaseous radionuclides were evaluated separately, as described in Section 3.2.2. These calculations were done under the assumption that gaseous radionuclides were released at a maximum rate, based on diffusion in the air filled pores and diluted into a 2 m atmospheric mixing zone. The total dose from volatile ^{3}H, ^{14}C, and ^{85}Kr combined was estimated to be less than 0.01 mrem at 100 years. Tritium and ^{85}Kr decay to negligible levels during the period of institutional control and ^{14}C doses are minimal due to the small site inventory. Combining the dose estimates for volatile and non-volatile radionuclides gives an estimated TEDE of 0.6 mrem yr^{-1} at 10,000 years and a conservative overestimate of 9.7 mrem yr^{-1} at the maximum, in approximately 700,000 years.

Intermediate results for the analyses above are presented in Appendix E. Soil activities and concentrations, calculated from the model described in Section 3.2.2.3, appear in Table E.4. Doses from inhalation and external exposure are listed in Tables E.6 and E.7.

4.1.2 Analysis Results for the Open Rangeland Scenario

The open rangeland scenario with an offsite ranch was described in Section 3.2.3.2. This scenario estimates the dose to members of the public residing offsite and using the RWMS to graze livestock. Doses have been evaluated at two offsite locations with sufficient water to support permanent residents. The closest offsite residents are assumed to be at Indian Springs during the 100-year institutional control period. Cane Springs, which is currently within the NTS boundary, is assumed to be available for development when institutional control ceases. During institutional control, exposure occurs through the atmospheric dispersion of contaminated soil and gaseous radionuclides. This is assumed to lead to contamination of air and soil at the offsite residence. The residents receive dose from external radiation from soils, inhalation of airborne radioactivity, and ingestion of foodstuffs grown at the offsite location. After institutional control ceases, the offsite resident continues

Table 4.2. continued.

Radionuclide	TEDE at 10,000 years		Maximum TEDE		
	Indian Springs	Cane Springs	Time of Maximum (years)	Indian Springs	Cane Springs
	(mrem yr^{-1})			(mrem yr^{-1})	
^{228}Ra+D	3.6×10^{-4}	3.6×10^{-4}	56,000	5.6×10^{-4}	5.6×10^{-4}
^{228}Th+D	1.5×10^{-6}	4.4×10^{-6}	56,000	2.3×10^{-6}	6.9×10^{-6}
^{241}Am	†	†	1,000	9.9×10^{-5}	1.0×10^{-4}
^{237}Np+D	9.0×10^{-5}	9.0×10^{-5}	53,000	1.6×10^{-4}	1.6×10^{-4}
Total	0.17	0.17		1.3‡	1.3‡

† - Maximum occurred before 10,000 years and dose at 10,000 years is negligible.
‡ - Total represents sum of maximum doses, which did not occur in the same years, and thus is an overestimate.

The maximum estimated TEDE within the 10,000-year compliance period is approximately 0.2 mrem yr^{-1} and occurs at the end of the interval. The doses at the two offsite locations are approximately equal because most of the dose is from ingestion of beef and milk produced at the RWMS. The nuclides with maximum doses before 10,000 years are ^{3}H, ^{14}C, ^{240}Pu, and ^{241}Am. Approximately 85 percent of the dose at 10,000 years is from ingestion of ^{238}U+D, ^{234}U, and ^{210}Pb+D in milk.

Most radionuclides reach a maximum soil concentration after the 10,000-year compliance interval because they are produced by radioactive decay of long-lived parents such as ^{238}U and ^{235}U. The maximum TEDE occurs between 600,000 and 700,000 years after closure and is slightly greater than 1 mrem yr^{-1}. Again, the doses are from ingestion of ^{238}U+D (6 percent), ^{234}U+D (6 percent), ^{226}Ra+D (15 percent), and ^{210}Pb+D (56 percent) in milk produced at the Area 5 RWMS.

The maximum TEDE from release of volatile radionuclides, excluding radon, are presented in Table 4.3. Under the conceptual model for release of gaseous radionuclides, the release rate decreases over time as nuclides decay. Therefore, the maximum doses within the compliance interval would occur at closure. The doses are estimated for Indian Springs. Table 4.3 shows that the estimated TEDE is much less than 0.001 mrem yr^{-1}. The distance to the nearest resident allows for significant dilution. Doses from ingestion of non-volatile ^{3}H and ^{14}C incorporated into milk and beef produced at the site are much greater than the dose from inhalation of volatile forms.

Table 4.3. Estimated maximum TEDE for volatile radionuclides (excluding radon). Maximum dose occurs at closure (i.e. at the beginning of the institutional control period when public access to the NTS is restricted).

Radionuclide	Release Rate ($Ci\ yr^{-1}$)	Offsite Air Concentration ($Ci\ m^{-3}$)†	TEDE ($mrem\ yr^{-1}$)
^{3}H	200	3.6×10^{-13}	2.9×10^{-4}
^{14}C	4.12‡	7.4×10^{-15}	1.5×10^{-6}
^{85}Kr	2.65×10^{-2} ‡	4.8×10^{-17}	6.7×10^{-10}

† - Evaluated at Indian Springs for the first year after closure (access to Cane Springs is assumed to be restricted at this time).
‡ - Represents release of entire inventory during the first year.

Intermediate results for the open rangeland scenario can be found in Appendix E. Offsite air concentrations at Indian Springs and Cane Springs appear in Table E.5. Doses by exposure pathway are given in Tables E.8 and E.9 of Appendix E.

4.1.3 Radon Flux from Shallow Land Burial Trenches and Pits

The CASCADR9 computer code has been used to estimate K_{SLB}, the ratio between ^{222}Rn surface flux and ^{226}Ra activity concentration for the shallow land burial geometry. The flux from shallow land burial trenches and pits (J_{SLB}) at any given time is:

$$J_{SLB} = 1 \times 10^{12}\ K_{SLB}\ C_{SLB}(t) \qquad (pCi\ m^{-2} s^{-1}) \tag{4.1}$$

where C_{SLB} is the shallow land burial ^{226}Ra activity concentration in units of $Ci\ m^{-3}$. The activity concentration of ^{226}Ra will increase very slowly over the next 10,000 years, not reaching a peak for several million years as shown in Figure 4.1. The predicted radon fluxes are presented in Table 4.4 and graphically in Figure 4.2. The flux remains below the performance objective of 20 $pCi\ m^{-2}\ s^{-1}$ throughout the 10,000-year compliance period. As shown in Figure 4.2, the flux exceeds the performance objective in approximately 30,000 years and reaches a peak of 156 $pCi\ m^{-2}\ s^{-1}$ in 3.5×10^{6} years. The flux results beyond 30,000 years are considered very conservative because they assume that cap thickness remains constant. In reality, closure caps should eventually be buried by accumulating sediments. It is likely that much more than 2.4 m of sediment will cover the site in 3.5×10^{6} years and that the actual peak fluxes will be much smaller than those predicted here for a 2.4 m cover. Approximately 4.5 m of cover would be required to attenuate the peak flux occurring at 3.5×10^{6} years to 20 $pCi\ m^{-2}\ s^{-1}$.

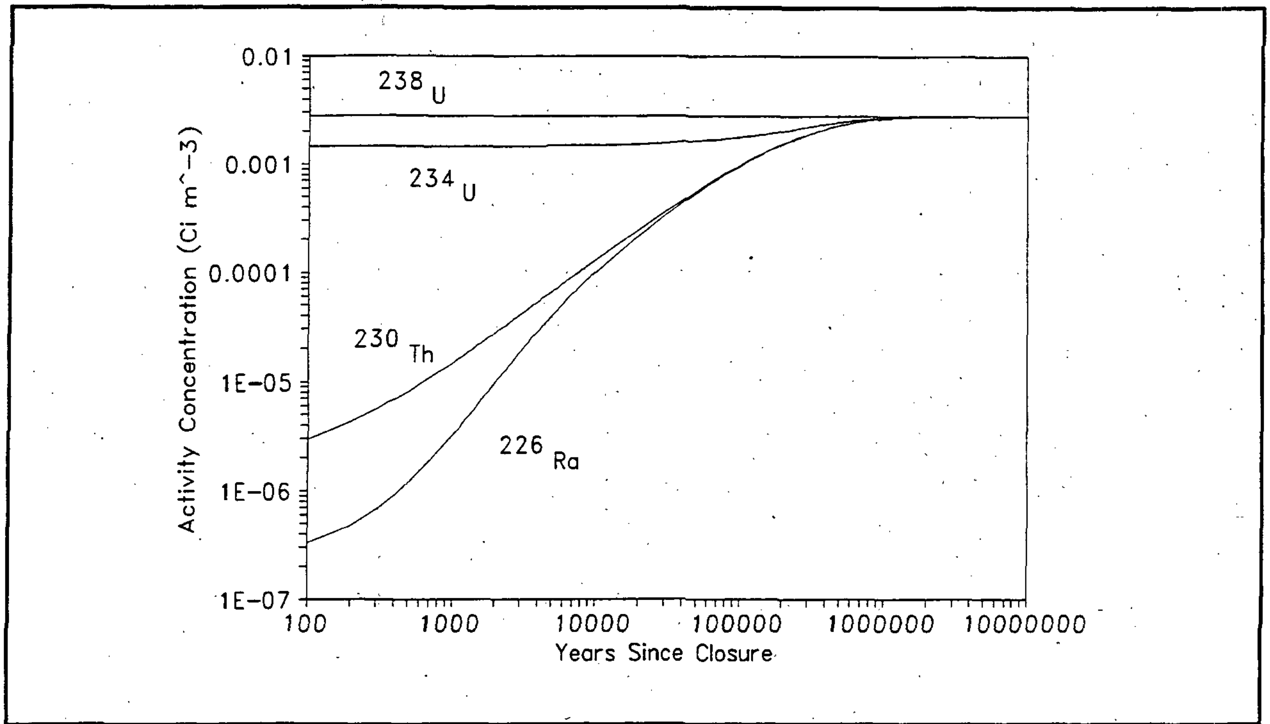


Figure 4.1 - Mean activity concentration of ^{226}Ra in shallow land burial trenches and pits.

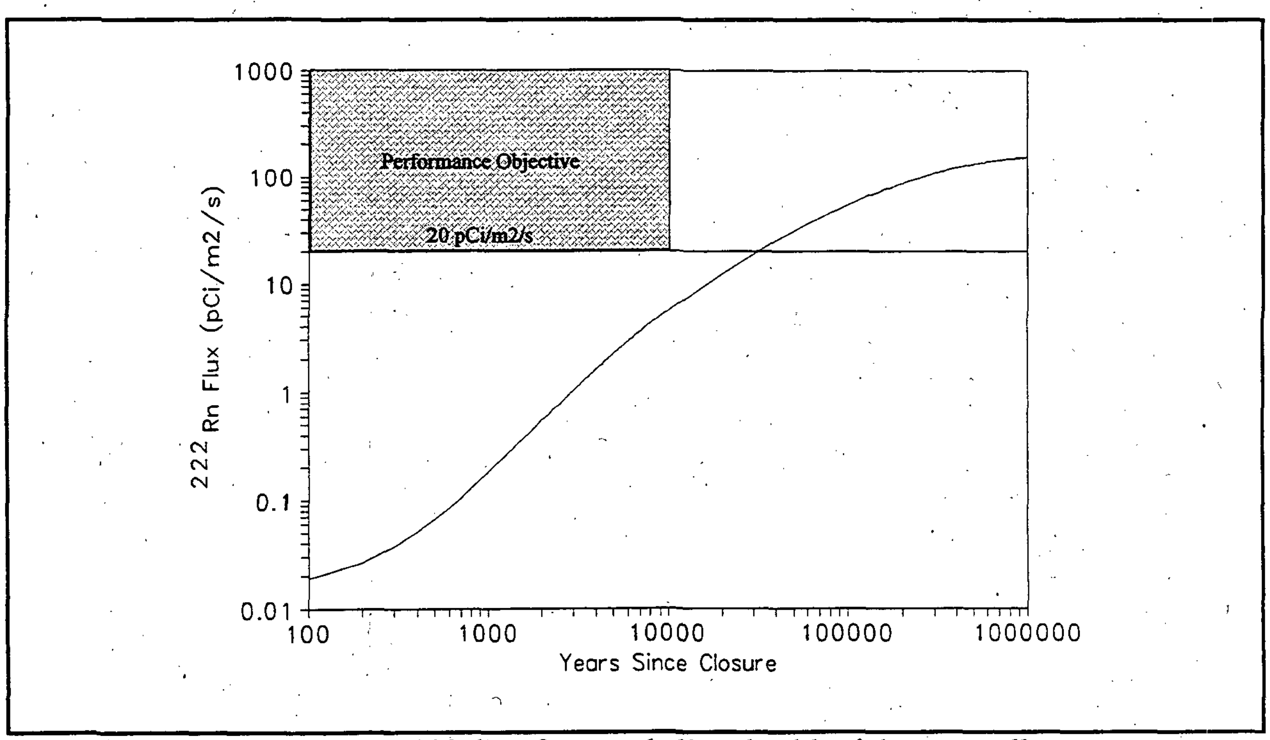


Figure 4.2 - Estimated radon-222 flux from a shallow land burial waste cell.

Table 4.4. Estimated radon flux from shallow land burial trenches and pits.

$K_{SLB} = 5.6 \times 10^{-8}$ m s^{-1}		
Years Since Closure	**^{226}Ra Activity Concentration (Ci m^{-3})**	**^{222}Rn Flux (pCi m^{-2} s^{-1})**
100	3.3×10^{-7}	0.018
10,000	1.0×10^{-4}	5.6
3.5×10^{6}	2.8×10^{-3}	156

From these data, waste concentrations yielding a flux of 20 pCi m^{-2} s^{-1} in 10,000 years for a shallow land burial cell can be estimated. The average waste concentration producing the flux limit can be estimated from:

$$C_L = \frac{1 \times 10^{-12}}{DF} \frac{F_L}{K_{SLB}} \quad (4.2)$$

where:

C_L	=	waste activity concentration limit,
DF	=	maximum fractional ingrowth of ^{226}Ra from parent in 10,000 years,
F_L	=	flux limit (20 pCi m^{-2} s^{-1}), and
K_{SLB}	=	radon flux rate per unit activity concentration, 5.6×10^{-8} m s^{-1}, for a 2.4 m cap.

The attenuation of a 4 m cap was also investigated, and the value of K_{SLB} was found to be 1.1×10^{-8} m s^{-1}. [illegible]

Table 4.5. continued.

Radionuclide	DF	Concentration Limit C_L ($Ci\ m^{-3}$)	
		2.4 m Cap	4.0 m Cap
^{230}Th	0.921	3.9×10^{-4}	1.8×10^{-3}
^{226}Ra	1	3.6×10^{-4}	1.7×10^{-3}

4.1.4 Estimated Radon Flux from Pit 6 (PO6U)

Pit 6 has been modified to accept a special case thorium waste stream containing ^{230}Th. A lower or deeper cell 3.6 m thick has been prepared for the thorium waste and an upper 6.2 m thick cell will be filled with routine LLW. CASCADR9 was used to develop a ratio between surface flux and activity concentration (K-factor) for each waste cell. The waste cells can be considered independently and the results summed to obtain the total flux. The peak ^{226}Ra activity concentrations occur at different times for different waste cells. This is due to differing initial concentrations of long-lived parent nuclides (Figures 4.1 and 4.3). When the thorium waste reaches its peak ^{226}Ra concentration in 9,000 years, the concentration of LLW in the upper cell is two orders of magnitude lower. The LLW in the upper cell will not reach its maximum concentration for several million years, when ^{230}Th in

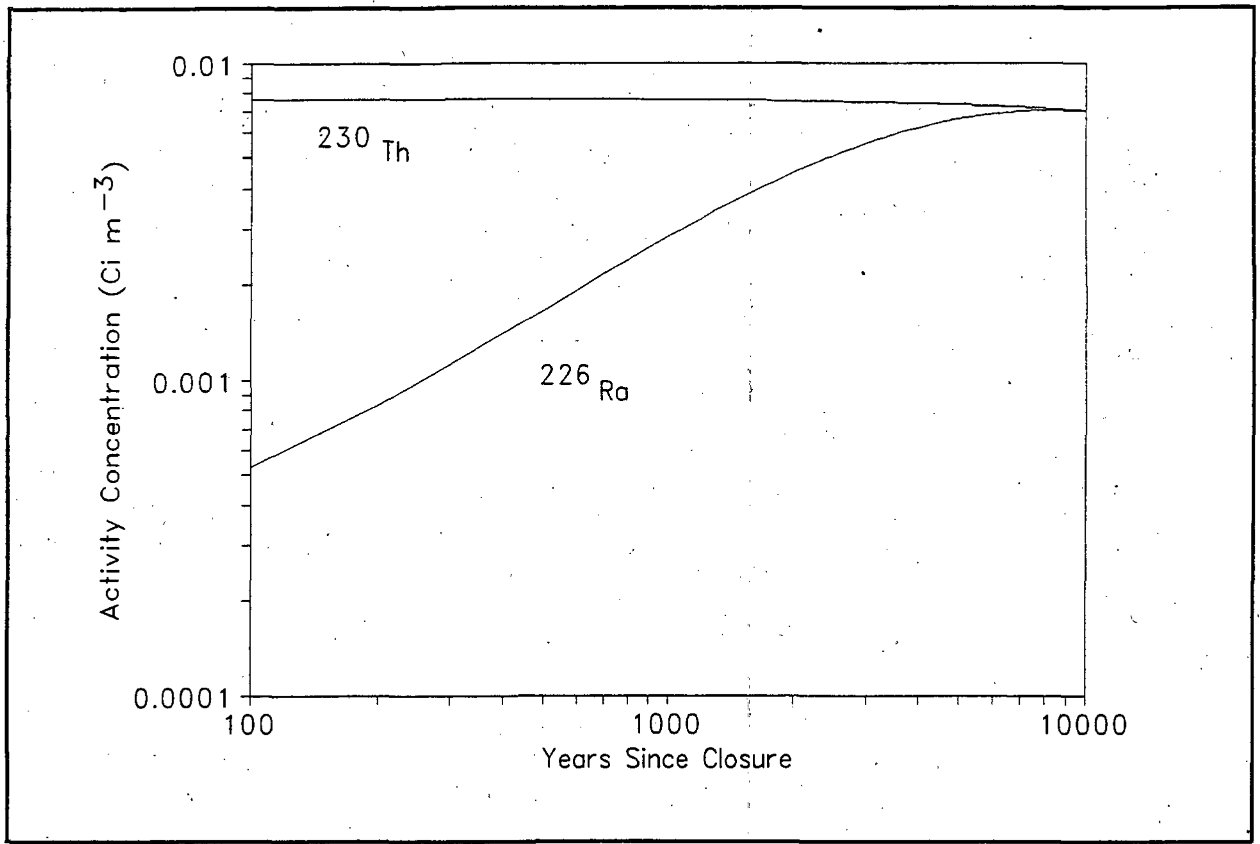


Figure 4.3 - Mean activity concentration of ^{226}Ra in the lower cell of Pit 6 for assumed concentration of special case thorium waste.

Total radon flux from Pit 6 in presented in Table 4.6 and in Figure 4.4. The total flux remains below the performance objective limit of 20 pCi m^{-2} s^{-1} during the entire 10,000-year compliance interval. For the first 700 years, the flux from each cell is approximately equal. After this time, the ^{222}Rn flux from the upper cell begins to exceed the flux from the Th waste and the predictions are very similar to those for the shallow land burial case. Although the ^{226}Ra source term in the special case Th waste is greater, the upper cell produces a greater flux because the burial is more shallow. By 10,000 years, the total flux reaches 5.5 pCi m^{-2} s^{-1}, approximately equal to the flux predicted for the shallow land burial case. The total flux exceeds the 20 pCi m^{-2} s^{-1} limit in approximately 30,000 years and reaches a peak in 3.5×10^6 years. Total fluxes beyond 30,000 years are likely to be less than estimated here because alluvial sediment accumulating at the site is likely to increase the overburden.

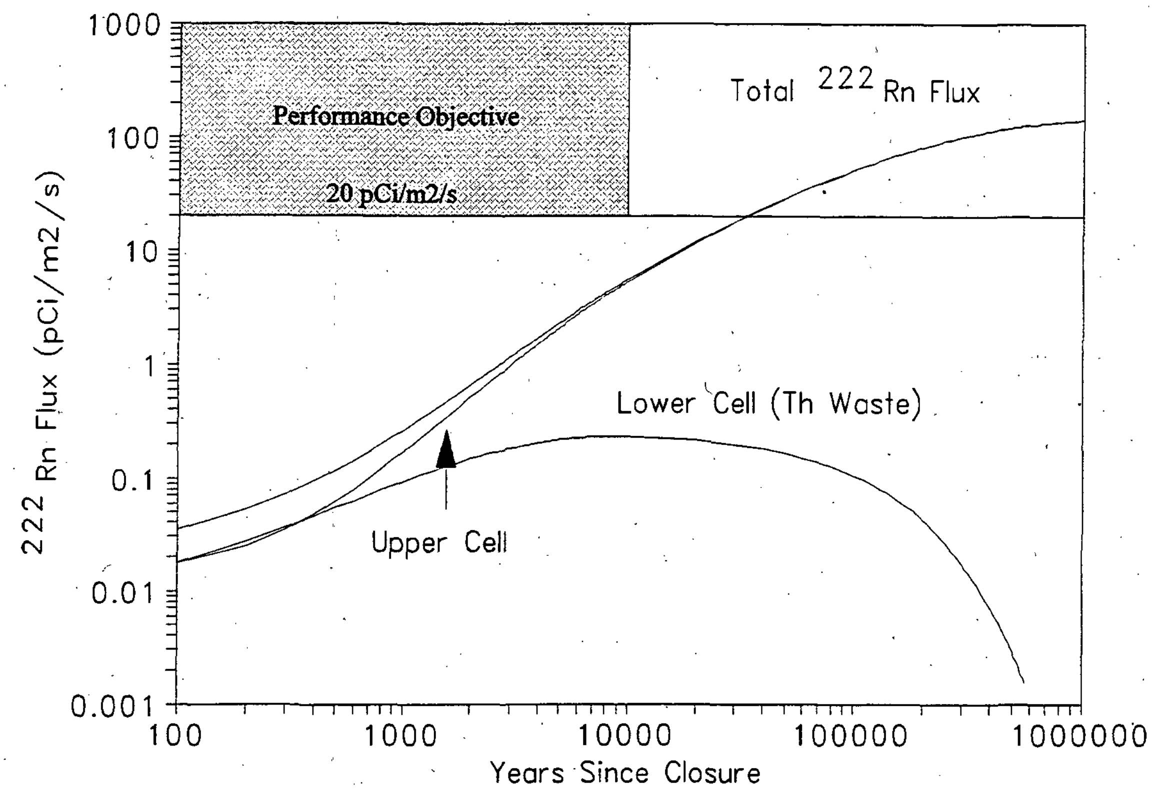


Figure 4.4 - Estimated total flux of ^{222}Rn from Pit 6.

Table 4.6. Estimated total ^{222}Rn flux from Pit 6 (PO6U).

Years Since Closure	$K_{P6U} = 5.3 \times 10^{-8}$ m s^{-1} Pit 6 Upper Cell ^{226}Ra Activity Conc. (Ci m^{-3})	$K_{P6L} = 3.3 \times 10^{-11}$ m s^{-1} Pit 6 Lower Cell ^{226}Ra Activity Conc. (Ci m^{-3})	Pit 6 Total ^{222}Rn Flux (pCi m^{-2} s^{-1})
100	3.3×10^{-7}	5.3×10^{-4}	0.035
9,000	8.7×10^{-5}	7.1×10^{-3}	4.9
10,000	1.0×10^{-4}	7.0×10^{-3}	5.6
3.5×10^{6}	2.8×10^{-3}	1.6×10^{-16}	147

4.2 ANALYSIS RESULTS FOR INTRUDER SCENARIOS

This section describes the results of intruder analyses. Intruder scenarios are hypothetical events analyzed to estimate the risk to persons intruding into buried waste after loss of institutional control. Intruder analyses are performed to determine the activity concentration of waste suitable for disposal in the near surface. Concentration limits based on the intruder analysis are described in this section. Three intruder analyses, one acute and two chronic, were analyzed: the drilling scenario (acute), the intruder-agriculture scenario (chronic), and post-drilling scenario (chronic). Two source terms were analyzed in the performance assessment, the inventory for shallow land burial pits and trenches and the inventory for Pit 6. Pit 6 includes a lower or deeper cell that will be used for disposal of special case thorium waste. Since intruder scenarios are hypothetical events involving few people, the dose limits are higher than permitted for members of the public. The dose limits for intruder scenarios are 500 mrem for an acute (short-term) scenario and 100 mrem yr^{-1} for a chronic scenario.

4.2.1 Analysis Results for the Acute Intruder Drilling Scenario

The intruder drilling scenario is a short-term exposure scenario that assumes an intruder is exposed to contaminated drill cuttings. Complete details of the scenario, conceptual models and assumptions, are provided in Section 3.3.1. The intruders are assumed exposed via inhalation of resuspended drill cuttings, inadvertent ingestion of cuttings, and external irradiation from the drilling fluids. The time of exposure is assumed to be 100 hours, approximately two weeks. The acute drilling scenario was analyzed for the shallow land burial inventory and for Pit 6. Results are presented for 100 years, 10,000 years, and, if occurring beyond 10,000 years, at the time of maximum dose. For nuclides with short-lived progeny that can be assumed to be in equilibrium, the dose from the progeny have been added to the dose from the parent. These nuclides are denoted "+D" throughout this report continues to increase with time, and by the time of the maximum dose at 3.5×10^6 years after closure, external irradiation from $^{226}Ra+D$ is the dominant contributor.

The upper and lower cells of the Pit 6 source term were analyzed separately and the results summed to obtain the total. The upper cell was assumed filled with waste having the same mean activity concentration as the shallow land burial inventory. However, this cell is 6.2 m thick, compared with the 4.9 m adopted for the shallow land burial trenches. The lower cell

waste received since FY89. The Pit 6 inventory was analyzed at 100 and 10,000 years. The dose from the inventory in the upper cell will peak at 3.5×10^6 years and be approximately

Table 4.7. Soil activity concentrations and TEDE for the acute drilling scenario with the shallow land burial inventory. Soil activity concentration is the estimated concentration of the drill cuttings created by the intruder.

Radionuclide	At 100 years		At 10,000 years		At Time of Maximum Dose		
	Soil Conc. (pCi g^{-1})	TEDE (mrem)	Soil Conc. (pCi g^{-1})	TEDE (mrem)	Time (years)	Soil Conc. (pCi g^{-1})	TEDE (mrem)
^{3}H	30	3.9×10^{-4}			100	30	3.9×10^{-4}
^{14}C	0.11	2.7×10^{-4}	0.033	8.1×10^{-5}	100	0.11	2.7×10^{-4}
^{36}Cl	4.1×10^{-9}	1.7×10^{-14}	4.0×10^{-9}	1.6×10^{-14}	100	4.1×10^{-9}	1.7×10^{-14}
^{59}Ni	6.2×10^{-7}	9.5×10^{-14}	5.7×10^{-7}	8.7×10^{-14}	100	6.2×10^{-7}	9.5×10^{-14}
^{60}Co	1.1×10^{-8}	4.4×10^{-10}			100	1.1×10^{-8}	4.4×10^{-10}
^{63}Ni	0.049	1.6×10^{-8}			100	0.049	1.6×10^{-8}
^{90}Sr+D	0.011	9.4×10^{-7}			100	0.011	9.4×10^{-7}
^{93}Zr+D	1.0×10^{-6}	6.2×10^{-12}	1.0×10^{-6}	6.2×10^{-12}	100	1.0×10^{-6}	6.2×10^{-12}
^{99}Tc	1.3×10^{-5}	9.4×10^{-12}	1.3×10^{-5}	9.1×10^{-12}	100	1.3×10^{-5}	9.4×10^{-12}
^{107}Pd	2.9×10^{-7}	6.9×10^{-14}	2.9×10^{-7}	6.9×10^{-14}	100	2.9×10^{-7}	6.9×10^{-14}
^{126}Sn+D	3.4×10^{-7}	4.3×10^{-8}	3.2×10^{-7}	4.0×10^{-8}	100	3.4×10^{-7}	4.3×10^{-8}
^{129}I	8.7×10^{-8}	2.5×10^{-11}	8.7×10^{-8}	2.5×10^{-11}	100	8.7×10^{-8}	2.5×10^{-11}
^{133}Ba	5.3×10^{-9}	4.7×10^{-11}			100	5.3×10^{-9}	4.7×10^{-11}
^{135}Cs	2.4×10^{-6}	8.3×10^{-12}	2.4×10^{-6}	8.1×10^{-12}	100	2.4×10^{-6}	8.3×10^{-12}
^{137}Cs+D	0.013	1.4×10^{-4}			100	0.013	1.4×10^{-4}

Table 4.7. continued.

Radionuclide	At 100 years		At 10,000 years		At Time of Maximum Dose		
	Soil Conc. (pCi g^{-1})	TEDE (mrem)	Soil Conc. (pCi g^{-1})	TEDE (mrem)	Time (years)	Soil Conc. (pCi g^{-1})	TEDE (mrem)
^{151}Sm	1.7×10^{-3}	9.5×10^{-10}			100	1.7×10^{-3}	9.5×10^{-10}
^{152}Eu	1.1×10^{-11}	2.0×10^{-13}			100	1.1×10^{-11}	2.0×10^{-13}
^{154}Eu	7.8×10^{-8}	1.6×10^{-9}			100	7.8×10^{-8}	1.6×10^{-9}
^{207}Bi	3.6×10^{-11}	7.5×10^{-13}			100	3.6×10^{-11}	7.5×10^{-13}
^{232}U	1.0×10^{-3}	9.6×10^{-6}			100	1.0×10^{-3}	9.6×10^{-6}
^{243}Am+D	2.3×10^{-5}	2.8×10^{-7}	9.0×10^{-6}	1.1×10^{-7}	100	2.3×10^{-5}	2.8×10^{-7}
^{239}Pu	3.1	0.028	2.3	0.021	100	3.1	0.028
^{235}U+D	0.80	3.8×10^{-3}	0.81	3.8×10^{-3}	450,000	0.80	3.8×10^{-3}
^{231}Pa	3.3×10^{-3}	7.6×10^{-5}	0.15	3.6×10^{-3}	450,000	0.80	0.018
$^{227}Ac+D$	2.8×10^{-3}	2.9×10^{-4}	0.15	0.016	450,000	0.80	0.083
^{241}Pu	0.027	4.8×10^{-6}			100	0.027	4.8×10^{-6}
^{241}Am	0.52	4.8×10^{-3}			100	0.52	4.8×10^{-3}
$^{237}Np+D$	2.3×10^{-4}	2.8×10^{-6}	3.1×10^{-4}	3.8×10^{-6}	4,600	3.3×10^{-4}	4.1×10^{-6}
^{233}U	3.4×10^{-5}	6.4×10^{-8}	4.6×10^{-5}	8.6×10^{-8}	640,000	2.6×10^{-4}	4.8×10^{-7}
$^{229}Th+D$	3.8×10^{-7}	1.2×10^{-8}	2.5×10^{-5}	8.2×10^{-7}	640,000	2.6×10^{-4}	8.4×10^{-6}
^{242}Pu	6.2×10^{-5}	5.2×10^{-7}	6.1×10^{-5}	5.1×10^{-7}	100	6.2×10^{-5}	5.2×10^{-7}

Table 4.7. continued.

Radionuclide	At 100 years		At 10,000 years		At Time of Maximum Dose		
	Soil Conc. ($pCi\ g^{-1}$)	TEDE (mrem)	Soil Conc. ($pCi\ g^{-1}$)	TEDE (mrem)	Time (years)	Soil Conc. ($pCi\ g^{-1}$)	TEDE (mrem)
^{238}U+D	27	0.054	27	0.054	3,500,000	27	0.054
^{238}Pu	1.5	0.012			100	1.5	0.012
^{234}U	14	0.027	14	0.027	3,500,000	27	0.051
^{230}Th	0.029	1.3×10^{-4}	1.2	5.7×10^{-3}	3,500,000	27	0.12
^{226}Ra+D	3.3×10^{-3}	8.9×10^{-5}	0.97	0.026	3,500,000	27	0.73
^{210}Pb+D	2.9×10^{-3}	9.7×10^{-6}	0.97	3.3×10^{-3}	3,500,000	27	0.091
^{244}Cm	3.6×10^{-4}	1.7×10^{-6}			100	3.6×10^{-4}	1.7×10^{-6}
^{248}Cm	1.8×10^{-11}	5.9×10^{-13}	1.7×10^{-11}	5.7×10^{-13}	100	1.8×10^{-11}	5.9×10^{-13}
^{240}Pu	0.65	5.7×10^{-3}	0.23	2.0×10^{-3}	100	0.65	5.7×10^{-3}
^{236}U	0.023	4.0×10^{-5}	0.023	4.0×10^{-5}	32,000	0.023	4.0×10^{-5}
^{232}Th	0.051	1.2×10^{-3}	0.050	1.1×10^{-3}	100	0.051	1.2×10^{-3}
^{228}Ra+D	0.051	7.7×10^{-4}	0.050	7.6×10^{-4}	100	0.051	7.7×10^{-4}
^{228}Th+D	0.051	1.2×10^{-3}	0.050	1.2×10^{-3}	100	0.051	1.2×10^{-3}
Total		0.15		0.17			

Table 4.8. Soil activity concentrations and TEDE for the acute drilling scenario for Pit 6 (PO6U) at 100 years. Soil activity concentration is the estimated concentration of the drill cuttings created by the intruder.

Table 4.8. continued.

Radionuclide	Upper Cell		Lower Cell		Total
	Soil Conc. ($pCi\ g^{-1}$)	TEDE (mrem)	Soil Conc. ($pCi\ g^{-1}$)	TEDE (mrem)	TEDE (mrem)
^{231}Pa	4.2×10^{-3}	9.6×10^{-5}			9.6×10^{-5}
$^{227}Ac+D$	3.5×10^{-3}	3.7×10^{-4}			3.7×10^{-4}
^{241}Pu	0.034	6.1×10^{-6}			6.1×10^{-6}
^{241}Am	0.66	6.1×10^{-3}			6.1×10^{-3}
$^{237}Np+D$	2.9×10^{-4}	3.5×10^{-6}			3.5×10^{-6}
^{233}U	4.3×10^{-5}	8.1×10^{-8}			8.1×10^{-8}
$^{229}Th+D$	4.8×10^{-7}	1.5×10^{-8}			1.5×10^{-8}
^{242}Pu	7.8×10^{-5}	6.6×10^{-7}			6.6×10^{-7}
$^{238}U+D$	34	0.068			0.068
^{238}Pu	1.9	0.015			0.015
^{234}U	18	0.034			0.034
^{230}Th	0.037	1.6×10^{-4}	55	0.25	0.25
$^{226}Ra+D$	4.2×10^{-3}	1.1×10^{-4}	3.8	0.10	0.10
$^{210}Pb+D$	3.7×10^{-3}	1.2×10^{-5}	3.1	0.010	0.010
^{244}Cm	4.6×10^{-4}	2.1×10^{-6}			2.1×10^{-6}
^{248}Cm	2.3×10^{-11}	7.5×10^{-13}			7.5×10^{-13}
^{240}Pu	0.82	7.2×10^{-3}			7.2×10^{-3}
^{236}U	0.029	5.1×10^{-5}			5.1×10^{-7}
^{232}Th	0.064	1.5×10^{-3}	355	8.1	8.1
$^{228}Ra+D$	0.064	9.7×10^{-4}	355	5.4	5.4
$^{228}Th+D$	0.064	1.5×10^{-3}	355	8.2	8.2
Total		0.18		22	22

Table 4.9. Soil activity concentrations and TEDE for the acute drilling scenario for Pit 6 (PO6U) at 10,000 years. Results for the lower cell are for 9,000 years, when the activity concentration of ^{226}Ra reaches its peak. Soil activity concentration is the estimated concentration of the drill cuttings created by the intruder.

Radionuclide	Upper Cell		Lower Cell		Total
	Soil Conc. ($pCi\ g^{-1}$)	TEDE (mrem)	Soil Conc. ($pCi\ g^{-1}$)	TEDE (mrem)	TEDE (mrem)
^{14}C	0.042	8.1×10^{-5}			8.1×10^{-5}
^{36}Cl	5.1×10^{-9}	2.0×10^{-14}			2.0×10^{-14}
^{59}Ni	7.2×10^{-7}	1.1×10^{-13}			1.1×10^{-13}
^{93}Zr+D	1.3×10^{-6}	7.8×10^{-12}			7.8×10^{-12}
^{99}Tc	1.6×10^{-5}	1.2×10^{-11}			1.2×10^{-11}
^{107}Pd	3.7×10^{-7}	8.7×10^{-14}			8.7×10^{-14}
^{126}Sn+D	4.0×10^{-7}	5.1×10^{-8}			5.1×10^{-8}
^{129}I	1.1×10^{-7}	3.2×10^{-11}			3.2×10^{-11}
^{135}Cs	2.9×10^{-6}	1.0×10^{-11}			1.0×10^{-11}
^{243}Am+D	1.1×10^{-5}	1.4×10^{-7}			1.4×10^{-7}
^{239}Pu	2.9	0.027			0.027
^{235}U+D	1.0	4.8×10^{-3}			4.8×10^{-3}
^{231}Pa	0.19	4.5×10^{-3}			4.5×10^{-3}
^{227}Ac+D	0.19	0.020			0.020
^{237}Np+D	3.9×10^{-4}	4.8×10^{-6}			4.8×10^{-6}
^{233}U	5.8×10^{-5}	1.1×10^{-7}			1.1×10^{-7}
^{229}Th+D	3.2×10^{-5}	1.0×10^{-6}			1.0×10^{-6}
^{242}Pu	7.7×10^{-5}	6.4×10^{-7}			6.4×10^{-7}
^{238}U+D	34	0.068			0.068
^{234}U	18	0.034			0.034
^{230}Th	1.5	7.2×10^{-3}	51	0.23	0.24
^{226}Ra+D	1.3	0.033	51	1.4	1.4

Table 4.9. continued.

	Upper Cell	Lower Cell	Total

Table 4.10. Soil activity concentrations and TEDE for the intruder-agriculture scenario with the shallow land burial inventory. Soil activity concentration is the estimated concentration of the surface contaminated zone created by the intruder.

Radionuclide	At 100 years		At 10,000 years		At Time of Maximum Dose		
	Soil Conc. ($pCi\ g^{-1}$)	TEDE ($mrem\ yr^{-1}$)	Soil Conc. ($pCi\ g^{-1}$)	TEDE ($mrem\ yr^{-1}$)	Time (years)	Soil Conc. ($pCi\ g^{-1}$)	TEDE ($mrem\ yr^{-1}$)
^{3}H	286	2.4			100	286	2.4
^{14}C	1.0	0.40	0.31	0.072	100	1.0	0.40
^{36}Cl	3.9×10^{-8}	4.9×10^{-8}	3.8×10^{-8}	4.8×10^{-8}	100	3.9×10^{-8}	4.9×10^{-8}
^{59}Ni	6.0×10^{-6}	3.3×10^{-10}	5.4×10^{-6}	3.0×10^{-10}	100	6.0×10^{-6}	3.3×10^{-10}
^{60}Co	1.0×10^{-7}	1.2×10^{-6}			100	1.0×10^{-7}	1.2×10^{-6}
^{63}Ni	0.47	6.7×10^{-5}			100	0.47	6.7×10^{-5}
^{90}Sr+D	0.11	0.13			100	0.11	0.13
^{93}Zr+D	9.6×10^{-6}	7.0×10^{-9}	9.6×10^{-6}	7.1×10^{-9}	100	9.6×10^{-6}	7.0×10^{-9}
^{99}Tc	1.3×10^{-4}	9.9×10^{-7}	1.2×10^{-4}	9.6×10^{-7}	100	1.3×10^{-4}	9.9×10^{-7}
^{107}Pd	2.8×10^{-6}	2.0×10^{-10}	2.8×10^{-6}	2.0×10^{-10}	100	2.8×10^{-6}	2.0×10^{-10}
^{126}Sn+D	3.3×10^{-6}	4.9×10^{-5}	3.1×10^{-6}	4.6×10^{-5}	100	3.3×10^{-6}	4.9×10^{-5}
^{129}I	8.3×10^{-7}	3.6×10^{-7}	8.3×10^{-7}	3.6×10^{-7}	100	8.3×10^{-7}	3.6×10^{-7}
^{133}Ba	5.1×10^{-8}	5.4×10^{-8}			100	5.1×10^{-8}	5.4×10^{-8}
^{135}Cs	2.4×10^{-5}	8.7×10^{-8}	2.4×10^{-5}	8.7×10^{-8}	100	2.4×10^{-5}	8.7×10^{-8}
^{137}Cs+D	0.13	0.36			100	0.13	0.36

Table 4.10. continued.

Radionuclide	At 100 years		At 10,000 years		At Time of Maximum Dose		
	Soil Conc. ($pCi\ g^{-1}$)	TEDE ($mrem\ yr^{-1}$)	Soil Conc. ($pCi\ g^{-1}$)	TEDE ($mrem\ yr^{-1}$)	Time (years)	Soil Conc. ($pCi\ g^{-1}$)	TEDE ($mrem\ yr^{-1}$)
^{151}Sm	0.017	5.6×10^{-7}			100	0.017	5.6×10^{-7}
^{152}Eu	1.1×10^{-10}	5.6×10^{-10}			100	1.1×10^{-10}	5.6×10^{-10}
^{154}Eu	7.5×10^{-7}	4.3×10^{-6}			100	7.5×10^{-7}	4.3×10^{-6}
^{207}Bi	3.4×10^{-10}	1.8×10^{-9}			100	3.4×10^{-10}	1.8×10^{-9}
^{232}U	9.6×10^{-3}	3.8×10^{-3}			100	9.6×10^{-3}	3.8×10^{-3}
^{243}Am+D	2.2×10^{-4}	3.0×10^{-4}	8.5×10^{-5}	1.2×10^{-4}	100	2.2×10^{-4}	3.0×10^{-4}
^{239}Pu	30	12	23	8.8	100	30	12
^{235}U+D	7.7	4.4	7.7	4.4	450,000	7.7	4.4
^{231}Pa	0.032	0.034	1.5	1.6	450,000	7.7	8.2
$^{227}Ac+D$	0.027	0.14	1.5	7.7	450,000	7.7	40
^{241}Pu	0.26	1.9×10^{-3}			100	0.26	1.9×10^{-3}
^{241}Am	5.0	4.0			100	5.0	4.0
$^{237}Np+D$	2.2×10^{-3}	0.037	3.0×10^{-3}	0.051	4,600	3.2×10^{-3}	0.054
^{233}U	3.3×10^{-4}	2.6×10^{-5}	4.4×10^{-4}	3.4×10^{-5}	640,000	2.5×10^{-3}	1.9×10^{-4}
$^{229}Th+D$	3.6×10^{-6}	8.2×10^{-6}	2.4×10^{-4}	5.4×10^{-4}	640,000	2.5×10^{-3}	5.5×10^{-3}
^{242}Pu	5.9×10^{-4}	2.2×10^{-4}	5.8×10^{-4}	2.1×10^{-4}	100	5.9×10^{-4}	2.2×10^{-4}

Table 4.10. continued.

Radionuclide	At 100 years		At 10,000 years		At Time of Maximum Dose		
	Soil Conc. ($pCi\ g^{-1}$)	TEDE ($mrem\ yr^{-1}$)	Soil Conc. ($pCi\ g^{-1}$)	TEDE ($mrem\ yr^{-1}$)	Time (years)	Soil Conc. ($pCi\ g^{-1}$)	TEDE ($mrem\ yr^{-1}$)
$^{238}U+D$	259	36	259	36	3,500,000	259	36
^{238}Pu	15	5.1			100	15	5.1
^{234}U	136	11	139	11	3,500,000	259	20
^{230}Th	0.28	0.048	12	2.1	3,500,000	259	45
$^{226}Ra+D$	0.031	0.25	9.3	76	3,500,000	259	2.1×10^{3}
$^{210}Pb+D$	0.028	0.011	9.3	3.6	3,500,000	259	100
^{244}Cm	3.4×10^{-3}	6.9×10^{-4}			100	3.4×10^{-3}	6.9×10^{-4}
^{248}Cm	1.7×10^{-10}	2.4×10^{-10}	1.7×10^{-10}	2.4×10^{-10}	100	1.7×10^{-10}	2.4×10^{-10}
^{240}Pu	6.2	2.4	2.2	0.85	100	6.2	2.2
^{236}U	0.22	0.016	0.22	0.016	32,000	0.22	0.016

where:

$C_{L,i}$ = concentration limit for nuclide i, Ci m^{-3},

H_L = intruder dose equivalent limit, 100 mrem yr^{-1},

$DCF_{Ag,j}$ = scenario dose conversion factor, mrem yr^{-1} per Ci m^{-3}, and

DF_j = maximum ratio of the activity of nuclide j to the initial activity of the long lived parent (nuclide i), dimensionless.

For radionuclides which decay to a stable progeny (i.e. i=j, n=0), DF_j is simply the fraction of the original activity remaining at the time of intrusion. For this assessment, the earliest time of intrusion has been assumed to be 100 years. However, limits for other times of intrusion have been developed for waste disposed of in the future that may have later probable intrusion times. A limit has been developed for intrusion at 200 years post-closure. It is reasonable to assume that a marker system installed at closure and maintained throughout the institutional control period would deter intrusion for at least an additional 100 years. The concentration limits for intrusion at 200 years are believed suitable for disposal below 2.4 m in a facility with a suitable marker system.

For radionuclides that decay to other radioactive elements (i.e. n>0), DF_j is the maximum activity of progeny produced within the compliance interval from a unit activity of the parent present at closure. The limits appearing in Table 4.11 were calculated under the assumption that the compliance interval is from the time of intrusion to 10,000 years. Proposed revisions to USDOE Order 5820.2A would limit compliance with the intruder performance objective to a period extending a few hundred years past closure. Implementation of this standard would allow an increase in waste concentration limits for those nuclides that will generate significant quantities of progeny within 10,000 years. Nuclides significantly affected by this change would be ^{234}U, ^{230}Th, ^{235}U, ^{231}Pa, and ^{233}U.

Table 4.11. Concentration limits for wastes disposed of below 2.4 m for various periods when intrusion may occur. The limits are derived from analysis of the intruder-agriculture scenario. Concentration limits for nuclides denoted "+D" include the contribution of progeny in equilibrium. The concentration limit applies to the parent only.

Radionuclide	Scenario Dose Conversion Factor (mrem yr^{-1} per Ci m^{-3})	Waste Concentration Limit (Ci m^{-3})	
		Intrusion at 100 to 10,000 years	Intrusion at 200 to 10,000 years
^{3}H	6.2×10^{2}	36	1.0×10^{4}
^{14}C	3.6×10^{4}	2.8×10^{-3}	2.8×10^{-3}

Table 4.11. continued.

	Scenario Dose	Waste Concentration Limit (Ci m^{-3})

Table 4.11. continued.

Radionuclide	Scenario Dose Conversion Factor (mrem yr^{-1} per Ci m^{-3})	Waste Concentration Limit (Ci m^{-3})	
		Intrusion at 100 to 10,000 years	Intrusion at 200 to 10,000 years
^{241}Am	7.5×10^4	1.6×10^{-3}	1.8×10^{-3}
$^{237}Np+D$	1.6×10^6	6.3×10^{-5}	6.3×10^{-5}
^{233}U	7.5×10^3	7.5×10^{-4}	7.5×10^{-4}
$^{229}Th+D$	2.1×10^5	4.8×10^{-4}	4.8×10^{-4}
^{242}Pu	3.5×10^4	2.9×10^{-3}	2.9×10^{-3}
$^{238}U+D$	1.3×10^4	7.2×10^{-3}	7.2×10^{-3}
^{238}Pu	3.3×10^4	6.7×10^{-3}	0.015
^{234}U	7.6×10^3	1.6×10^{-3}	1.6×10^{-3}
^{230}Th	1.6×10^4	1.4×10^{-4}	1.4×10^{-4}
$^{226}Ra+D$	7.5×10^5	1.3×10^{-4}	1.4×10^{-4}
$^{210}Pb+D$	3.7×10^4	0.060	1.4
^{244}Cm	1.9×10^4	0.20	0.95
^{248}Cm	1.3×10^5	7.7×10^{-4}	7.7×10^{-4}
^{240}Pu	3.6×10^4	2.8×10^{-3}	2.8×10^{-3}
^{236}U	6.9×10^3	0.014	0.014
^{232}Th	8.0×10^4	9.0×10^{-5}	9.0×10^{-5}
$^{228}Ra+D$	4.0×10^5	13	2.2×10^6
$^{228}Th+D$	6.3×10^5	No Limit	No Limit

4.2.3 Analysis Results for the Chronic Post-Drilling Scenario

The intruder post-drilling scenario assumes that an intruder builds a residence on an area contaminated with drill cuttings from the disposal site. As in the intruder-agriculture scenario, the intruder produces meat, milk, fruit, and vegetables within the contaminated zone. A complete description of the models and assumptions for the post-drilling scenario are presented in Section 3.2.2. The post-drilling scenario is the same as the intruder-agriculture scenario except for differences in the activity concentration and thickness of the contaminated zone. The post-drilling scenario applies to a greater source term because a borehole may penetrate any waste cell between the surface and the aquifer. Therefore, the

scenario was analyzed for a shallow land burial trench and Pit 6. The scenario was assumed to occur between 100 years and 10,000 years. The waste is assumed to be indistinguishable from soil at this time. Results from the post-drilling scenario were used to develop concentration limits for wastes disposed of below 4 m. Common construction excavations are unlikely to extend below 4 m.

The estimated TEDE at 100 years was 0.70 mrem yr^{-1} for a post-drilling intruder penetrating a shallow land burial trench (Table 4.12). Approximately 49 percent of the dose is due to inhalation of ^{3}H and ^{14}C released from the buried waste. The remainder of the dose is from exposure to the waste exhumed by the intruder. The contribution of the pathways was 25 percent from inhalation of resuspended activity, 16 percent from external irradiation, 6 percent from soil ingestion, and 2 percent from ingestion of agricultural products. The important nuclides and pathways for the exhumed waste are essentially the same as for the intruder-agriculture scenario, since the source term and pathway parameters are equivalent. The post-drilling scenario differs from the intruder-agriculture scenario in the greater relative contribution of volatile ^{3}H and ^{14}C released from the waste. At 10,000 years, the dose increases slightly to 0.71 mrem yr^{-1}. By 10,000 years, the dose from the release of volatile ^{3}H and ^{14}C is negligible. However, this decrease is offset by increasing external irradiation from ^{226}Ra+D.

Results for the post-drilling scenario applied to Pit 6 were obtained by summing the results for a 6.2 m thick shallow land burial trench with the results for the lower cell filled with thorium special case waste (Tables 4.13 and 4.14). The estimated total TEDE at 100 years was 163 mrem yr^{-1}. The thorium waste in the lower cell contributes 99 percent of the predicted dose. The dose is largely attributable to external irradiation from ^{228}Th+D

Table 4.12. Soil activity concentrations and TEDE for the post-drilling scenario with the shallow land burial inventory. Soil activity concentration is the estimated concentration of the surface contaminated zone created by the intruder.

Radionuclide	At 100 years		At 10,000 years		At Time of Maximum Dose		
	Soil Conc. ($nCi\ g^{-1}$)	TEDE ($mrem\ yr^{-1}$)	Soil Conc. ($nCi\ g^{-1}$)	TEDE ($mrem\ yr^{-1}$)	Time (years)	Soil Conc. ($nCi\ g^{-1}$)	TEDE ($mrem\ yr^{-1}$)

Table 4.12. continued.

Radionuclide	At 100 years		At 10,000 years		At Time of Maximum Dose		
	Soil Conc. ($pCi\ g^{-1}$)	TEDE ($mrem\ yr^{-1}$)	Soil Conc. ($pCi\ g^{-1}$)	TEDE ($mrem\ yr^{-1}$)	Time (years)	Soil Conc. ($pCi\ g^{-1}$)	TEDE ($mrem\ yr^{-1}$)
^{152}Eu	5.0×10^{-13}	2.3×10^{-12}			100	5.0×10^{-13}	2.3×10^{-12}
^{154}Eu	3.4×10^{-9}	1.7×10^{-8}			100	3.4×10^{-9}	1.7×10^{-8}
^{207}Bi	1.6×10^{-12}	7.6×10^{-12}			100	1.6×10^{-12}	7.6×10^{-12}
^{232}U	4.4×10^{-5}	1.7×10^{-5}			100	4.4×10^{-5}	1.7×10^{-5}
^{243}Am+D	1.0×10^{-6}	1.2×10^{-6}	3.9×10^{-7}	4.8×10^{-7}	100	1.0×10^{-6}	1.2×10^{-6}
^{239}Pu	0.14	0.053	0.10	0.040	100	0.14	0.053
^{235}U+D	0.036	0.020	0.036	0.020	450,000	0.036	0.020
^{231}Pa	1.5×10^{-4}	1.6×10^{-4}	6.8×10^{-3}	7.2×10^{-3}	450,000	0.036	0.038

Table 4.12. continued.

Radionuclide	At 100 years		At 10,000 years		At Time of Maximum Dose		
	Soil Conc. ($pCi\ g^{-1}$)	TEDE ($mrem\ yr^{-1}$)	Soil Conc. ($pCi\ g^{-1}$)	TEDE ($mrem\ yr^{-1}$)	Time (years)	Soil Conc. ($pCi\ g^{-1}$)	TEDE ($mrem\ yr^{-1}$)
^{234}U	0.63	0.049	0.64	0.050	3,500,000	1.2	0.093

Table 4.13. Soil activity concentrations and TEDE for the post-drilling scenario for Pit 6 (PO6U) at 100 years. Soil activity concentration is the estimated concentration of the surface contaminated zone created by the intruder.

Radionuclide	Upper Cell		Lower Cell		Total
	Soil Conc. (pCi g^{-1})	TEDE (mrem yr^{-1})	Soil Conc. (pCi g^{-1})	TEDE (mrem yr^{-1})	TEDE (mrem yr^{-1})
^{3}H	1.6	0.16			0.16
^{14}C	6.1×10^{-3}	0.18			0.18
^{36}Cl	2.3×10^{-10}	1.8×10^{-10}			1.8×10^{-10}
^{59}Ni	3.4×10^{-8}	1.5×10^{-12}			1.5×10^{-12}
^{60}Co	6.1×10^{-10}	6.3×10^{-9}			6.3×10^{-9}
^{63}Ni	2.8×10^{-3}	2.9×10^{-7}			2.9×10^{-7}
^{90}Sr+D	6.4×10^{-4}	4.7×10^{-4}			4.7×10^{-4}
^{93}Zr+D	6.1×10^{-8}	3.3×10^{-11}			3.3×10^{-11}
^{99}Tc	7.5×10^{-7}	3.8×10^{-9}			3.8×10^{-9}
^{107}Pd	1.6×10^{-8}	1.0×10^{-12}			1.0×10^{-12}
^{126}Sn+D	1.9×10^{-8}	2.8×10^{-7}			2.8×10^{-7}
^{129}I	4.9×10^{-9}	1.5×10^{-9}			1.5×10^{-9}
^{133}Ba	2.9×10^{-10}	3.2×10^{-10}			3.2×10^{-10}
^{135}Cs	1.4×10^{-8}	4.2×10^{-10}			4.2×10^{-10}
^{137}Cs+D	7.6×10^{-4}	1.9×10^{-3}			1.9×10^{-3}
^{151}Sm	9.7×10^{-5}	3.2×10^{-9}			3.2×10^{-9}
^{152}Eu	6.3×10^{-13}	2.9×10^{-12}			2.9×10^{-12}
^{154}Eu	4.3×10^{-9}	2.1×10^{-8}			2.1×10^{-8}
^{207}Bi	2.0×10^{-12}	9.6×10^{-12}			9.6×10^{-12}
^{232}U	5.6×10^{-5}	2.3×10^{-5}			2.3×10^{-5}
^{243}Am+D	1.3×10^{-6}	1.5×10^{-6}			1.5×10^{-6}
^{239}Pu	0.18	0.067			0.067
^{235}U+D	0.045	0.025			0.025

Table 4.13. continued.

Radionuclide	Upper Cell		Lower Cell		Total
	Soil Conc.	TEDE	Soil Conc.	TEDE	TEDE

Table 4.14. Soil activity concentrations and TEDE for the post-drilling scenario for Pit 6 (PO6U) at 10,000 years. Soil activity concentration is the estimated concentration of the surface contaminated zone created by the intruder.

Radionuclide	Upper Cell		Lower Cell		Total
	Soil Conc. ($pCi\ g^{-1}$)	TEDE ($mrem\ yr^{-1}$)	Soil Conc. ($pCi\ g^{-1}$)	TEDE ($mrem\ yr^{-1}$)	TEDE ($mrem\ yr^{-1}$)
^{14}C	1.8×10^{-3}	0.068			0.068
^{36}Cl	2.3×10^{-10}	1.8×10^{-10}			1.8×10^{-10}
^{59}Ni	3.2×10^{-8}	1.4×10^{-12}			1.4×10^{-12}
^{93}Zr+D	6.1×10^{-8}	3.3×10^{-11}			3.3×10^{-11}
^{99}Tc	7.2×10^{-7}	3.7×10^{-9}			3.7×10^{-9}
^{107}Pd	1.6×10^{-8}	1.0×10^{-12}			1.0×10^{-12}
^{126}Sn+D	1.8×10^{-8}	2.7×10^{-7}			2.7×10^{-7}
^{129}I	4.9×10^{-9}	1.5×10^{-9}			1.5×10^{-9}
^{135}Cs	7.6×10^{-8}	2.3×10^{-10}			2.3×10^{-10}
^{243}Am+D	4.9×10^{-7}	6.1×10^{-7}			6.1×10^{-7}
^{239}Pu	0.13	0.051			0.051
^{235}U+D	0.045	0.025			0.025
^{231}Pa	8.6×10^{-3}	9.3×10^{-3}			9.3×10^{-3}
$^{227}Ac+D$	8.6×10^{-3}	0.044			0.044
$^{237}Np+D$	1.8×10^{-5}	1.9×10^{-4}			1.9×10^{-4}
^{233}U	2.5×10^{-6}	2.0×10^{-7}			2.0×10^{-7}

Table 4.14. continued.

Radionuclide	Upper Cell		Lower Cell		Total
	Soil Conc. ($pCi\ g^{-1}$)	TEDE ($mrem\ yr^{-1}$)	Soil Conc. ($pCi\ g^{-1}$)	TEDE ($mrem\ yr^{-1}$)	TEDE ($mrem\ yr^{-1}$)
^{248}Cm	9.7×10^{-13}	1.4×10^{-12}			1.4×10^{-12}
^{240}Pu	0.013	4.9×10^{-3}			4.9×10^{-3}
^{236}U	1.3×10^{-3}	9.2×10^{-5}			9.2×10^{-5}
^{232}Th	2.8×10^{-3}	2.4×10^{-3}	16	14	14
$^{228}Ra+D$	2.8×10^{-3}	0.011	16	59	59
$^{228}Th+D$	2.8×10^{-3}	0.015	16	87	87
Total		0.90		177	178

The results from the post-drilling scenario were used to develop waste concentration limits for waste disposed of at depths greater than 4 m (Table 4.15). These limits were developed using the method described in Section 3.2.2 (Equation 4.4) for the intruder-agriculture scenario. An additional limit was set for an intrusion time of 500 years. This limit is appropriate for wastes having a form that would be resistant to intrusion for 500 years, such as those disposed of in high integrity containers.

Table 4.15. Concentration limits for wastes disposed of below 4 m at various times of intrusion. The limits are derived from analysis of the post-drilling intruder scenario. Concentration limits for nuclides denoted "+D" include the contribution of progeny in equilibrium. The concentration limit applies to the parent only.

Radionuclide	Scenario Dose Conversion Factor ($mrem\ yr^{-1}$ per $Ci\ m^{-3}$)	Waste Concentration Limit ($Ci\ m^{-3}$)		
		100 to 10,000 years	200 to 10,000 years	500 to 10,000 years
^{3}H	42	5.4×10^{2}	1.5×10^{5}	No Limit
^{14}C	1.6×10^{4}	6.2×10^{-3}	6.3×10^{-3}	6.5×10^{-3}
^{36}Cl	3.3×10^{2}	0.30	0.30	0.30
^{59}Ni	0.019	5.3×10^{3}	5.3×10^{3}	5.3×10^{3}
^{60}Co	4.5×10^{3}	1.1×10^{4}	No Limit	No Limit

Table 4.15. continued.

Table 4.15. continued.

Radionuclide	Scenario Dose Conversion Factor (mrem yr^{-1} per Ci m^{-3})	Waste Concentration Limit (Ci m^{-3})		
		100 to 10,000 years	200 to 10,000 years	500 to 10,000 years
$^{229}Th+D$	9.2×10^{2}	0.11	0.11	0.11
^{242}Pu	1.6×10^{2}	0.64	0.64	0.64
$^{238}U+D$	58	1.6	1.6	1.6
^{238}Pu	1.5×10^{2}	1.5	3.3	35
^{234}U	34	0.40	0.40	0.40
^{230}Th	74	0.034	0.034	0.034
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Table 4.16. continued.

Radionuclide	Scenario Dose Conversion Factor (mrem yr^{-1} per Ci m^{-3})	Waste Concentration Limit (Ci m^{-3})		
		100 to 10,000 years	200 to 10,000 years	500 to 10,000 years
^{230}Th	55	0.045	0.045	0.045
$^{226}Ra+D$	2.3×10^3	0.045	0.046	0.052
$^{210}Pb+D$	1.1×10^2	21	4.7×10^2	5.4×10^6

4.2.4 Doses to Intruders from Inhalation of Progeny of ^{222}Rn

An intruder residing over a waste disposal cell will be exposed to radon progeny released from the contaminated zone at the surface and from the buried waste. Analysis of the doses from each source indicates that the dose from the contaminated zone is negligible compared to that from the waste zone for depths of burial up to at least 4.5 m. The CEDE from ^{222}Rn progeny released from the buried waste at 100 years remains below 20 mrem yr^{-1} for all the configurations tested (Table 4.17), including cases with as little as 2.4 m of cap material present. Compliance with the limit at 10,000 years appears to require between 4 and 4.5 m of fill between the waste and the lowest point of the foundation.

Table 4.17. Estimated radon-222 dose results for intruders residing over a shallow land burial trench.

Cap Thickness	Foundation	CEDE (mrem yr^{-1})		
		100 years	10,000 years	3.5×10^6 years
2.4 m	Slab	1.7	510	1.4×10^4
2.4 m	2.8 m Basement	17	5.1×10^3	1.5×10^5
4.0 m	Slab	0.36	107	2.9×10^3
4.0 m	2.8 m Basement	5.3	1.6×10^3	4.4×10^4
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

4.3 SENSITIVITY AND UNCERTAINTY ANALYSIS

4.3.1 Sensitivity Analysis for the All-Pathways Scenarios

The dose to members of the general public is directly related to the predicted shallow soil concentration above the RWMS facility. The concentration of radionuclides in air, vegetables, milk, and beef pathways is a first order function of the surface soil concentration. Therefore the dose, both onsite and offsite, is also a first order function of shallow soil concentration.

Shallow soil concentration, as indicated by Equation 3.23 through 3.25, is a function of the input rates to the shallow surface soil compartment and the output rates, as defined in Section 3.2.2. The input rates of non-volatile radionuclides to the shallow soil, where they become

The results presented for ^{226}Ra in Table 4.18 indicate that the activity released is fairly insensitive to parameters in the root uptake model and most sensitive to the burrowing animal transfer rate, K_{b1}. This parameter represents the movement of radionuclides from the waste to the shallow soil. The model for ^{226}Ra was also found to be sensitive to the resuspension rate, K_s, representing fractional loss from the soil compartment. Root uptake parameters are less important for ^{226}Ra, because the parameters defining K_{r1}, which include the radionuclide-specific parameter B_{iv}, are relatively low for this radionuclide. Table 4.18 suggests that, for ^{226}Ra, *the soil activity is linearly related to* K_{b1}, *which according to Equation 3.21, is linearly* related to the amount of soil excavated by ants in the waste zone and the burrower colony density, both of which are highly uncertain. Sensitivity of ^{226}Ra to the resuspension rate is suppressed by the value of the radioactive decay constant, which is approximately 4×10^{-4} yr^{-1}. A longer-lived radionuclide would show a greater sensitivity to the resuspension rate, which would then control loss from the shallow soil compartment.

Table 4.18. Results of the sensitivity analysis for ^{226}Ra in the base case release model.

Parameter	Parameter Value (yr^{-1})	Maximum ^{226}Ra Shallow Soil Activity† (Ci)
Base Case	-----	1.0×10^{-4}
K_s	1.0×10^{-5} §	1.1×10^{-4}
K_s	1.0×10^{-3} ‡	5.7×10^{-5}
K_{b1}	1.3×10^{-6} ‡	1.0×10^{-3}
K_{b1}	1.3×10^{-8} §	1.1×10^{-5}
K_{b2}	1.8×10^{-6} ‡	1.0×10^{-4}
K_{b2}	1.8×10^{-8} §	1.0×10^{-4}
K_{r1}	1.3×10^{-8} ‡	1.1×10^{-4}
K_{r1}	1.3×10^{-10} §	1.0×10^{-4}
K_{r2}	5.4×10^{-9} ‡	1.0×10^{-4}
K_{r2}	5.4×10^{-11} §	1.0×10^{-4}
K_{r3}	3.8×10^{-7} ‡	1.0×10^{-4}
K_{r3}	3.8×10^{-9} §	1.0×10^{-4}

† Per unit activity (Ci) in waste.
‡ Value is a factor of ten higher than the base case; all other parameters the same as the base case.
§ Value is a factor of ten lower than the base case; all other parameters the same as the base case.

The results of the sensitivity analysis for ^{14}C are presented in Table 4.19. Carbon-14 was selected to represent a nuclide with a high plant-soil concentration factor. Carbon was assumed to be in a non-volatile form in this analysis.

Table 4.19. Results of sensitivity analysis for non-volatile ^{14}C in the base case release model.

Parameter	Parameter Value (yr^{-1})	Maximum ^{14}C Surface Soil Activity† (Ci)
Base Case	-----	4.7×10^{-3}
K_s	1.0×10^{-5} §	6.3×10^{-3}
K_s	1.0×10^{-3} ‡	1.4×10^{-3}
K_{b1}	1.3×10^{-6} ‡	5.7×10^{-3}
K_{b1}	1.3×10^{-8} §	4.6×10^{-3}
K_{b2}	1.8×10^{-6} ‡	5.0×10^{-3}
K_{b2}	1.8×10^{-8} §	4.6×10^{-3}
K_{r1}	4.9×10^{-5} ‡	3.7×10^{-2}
K_{r1}	4.9×10^{-7} §	9.8×10^{-4}
K_{r2}	1.8×10^{-5} ‡	7.7×10^{-3}
K_{r2}	1.8×10^{-7} §	4.4×10^{-3}
K_{r3}	7.4×10^{-4} ‡	5.7×10^{-3}
K_{r3}	7.4×10^{-6} §	4.3×10^{-3}

† Per unit activity (Ci) in waste.
‡ Value is a factor of ten higher than the base case; all other parameters the same as the base case.
§ Value is a factor of ten lower than the base case; all other parameters the same as the base case.

The sensitivity analysis for ^{14}C, a nuclide with a high plant-soil concentration factor, shows that the root transfer rate, K_{r1}, is the most sensitive parameter. The surface soil concentration is approximately proportional to K_{r1}, the root transfer factor from the waste to the surface soil. From Equation 3.17, it can be seen that K_{r1} is the product of the plant-soil concentration factor and several poorly-known biological factors, such as plant productivity and rooting depth. As expected, the sensitivity to the resuspension factor is greater for ^{14}C

4.3.2 Radon Flux Sensitivity and Uncertainty Analysis

Lindstrom et al. (1994) has performed a sensitivity analysis of CASCADR9 that considered source term concentration, background radon concentration, half-life, porosity, period and amplitude of the atmospheric pressure wave, and eddy diffusivity of the atmosphere soil mixing layer. The most important parameters for cases where the source term was larger than the background concentration, in decreasing order of significance, were porosity, half-life, and source term concentration. The uncertainty in radiological half-life was assumed to be negligible and its effect was not examined. Uncertainty in radon flux results was assessed by setting the porosity and ^{226}Ra source term to bounding values and examining the effect on flux. In addition, since thickness of the waste layer was not considered by Lindstrom et al. (1994), a bounding case with maximum waste thickness for the Area 5 RWMS (PO3U) was considered to assess the importance of thicker waste layers.

Uncertainty in the radon results for the shallow land burial waste cells was assessed by varying waste cell thickness, waste porosity, soil porosity, and radium inventory. Waste cell thickness is not constant for all pits and trenches at the Area 5 RWMS. A single case (Case 1) was run to assess the importance of waste cell thickness. The thickness used, 7.9 m, corresponds to the thickest cell constructed at the RWMS, Pit 3 (PO3U). The results indicate that the K_{SLB} factor decreases slightly with the increase in thickness from 4.9 to 7.9 m (Table 4.20). It was concluded that waste cell thickness over the range of values observed at the RWMS has a negligible effect on radon flux uncertainty. Three cases were run to assess the significance of uncertainty in porosity (Table 4.20). The porosity values selected represent the bounding values for both soil and waste. The maximum porosity observed for shallow alluvium is approximately 0.50 (REECo, 1993c). For the waste, lower porosity will increase the flux by increasing the concentration of the gas source term. The lowest reasonable porosity value for waste was assumed to be the same as that of the alluvium, 0.36. Since radon flux will scale linearly with the radium concentration, specific modeling cases were not analyzed.

Table 4.20. Uncertainty cases and results for the radon K-factors for shallow land burial. Varied parameters are listed. All other parameters are as in the base case (see Table 3.11).

Table 4.20. continud.

Uncertainty Case	Waste Cell Thickness (m)	Cap Porosity	Waste Porosity	K_{SLB} Factor ($m\ s^{-1}$)
Case 2b	4.9	0.36	0.36	1.4×10^{-7}
Case 2c	4.9	0.50	0.36	2.3×10^{-7}

The uncertainty in radon flux from Pit 6 was assessed in a similar fashion (Table 4.21). The porosity of similar material was always assumed to be the same; that is, the cap and backfill soil porosities are always the same, and the upper and lower cell waste porosities are always the same. The selected combinations represent bounding values.

Table 4.21. Uncertainty cases and results for radon K-factors for Pit 6 (PO6U). Varied parameters are listed. All other parameters are as in the base case (see Table 3.11).

Uncertainty Case	Cap Porosity	Upper Cell Waste Porosity	Soil Backfill Porosity	Lower Waste Cell Porosity	K_{P6U} Factor ($m\ s^{-1}$)	K_{P6L} Factor ($m\ s^{-1}$)
Case 3a	0.50	0.67	0.50	0.67	1.1×10^{-7}	2.3×10^{-10}
Case 3b	0.36	0.36	0.36	0.36	1.4×10^{-7}	2.7×10^{-11}
Case 3c	0.50	0.36	0.50	0.36	2.7×10^{-7}	8.7×10^{-11}

Radon fluxes for two bounding cases for the shallow land burial cells are presented in Table 4.22. Case 2b, representing a combination of the best estimate alluvium porosity and worst case waste porosity, meets the flux standard. Case 2c, which includes the worst case porosity for alluvium and waste, fails to meet the flux standard. The alluvium porosity is very well known from site characterization studies and can be controlled through design specifications. Therefore, case 2b is believed to be a more credible bounding case for shallow land burial. Similar conclusions can be drawn for the Pit 6 cases. The radon flux scales linearly with ^{226}Ra source term concentration. Since the 10,000 year flux for the base case was estimated to be 5.6 pCi $m^{-2}\ s^{-1}$, an underestimate of the source term concentration by a factor of four would be sufficient to exceed the limit. Uranium-234 will be a major source of ^{226}Ra over the next 10,000 years and is believed to be underreported in the site inventory. However, the site inventory was revised upward by more than a factor of two to correct for underreporting. It is unlikely that a factor of four uncertainty remains in the activity of ^{234}U. Therefore, source term uncertainty alone does not appear to be sufficient to cause the limit to be exceeded. Credible uncertainty cases for porosity do not appear sufficient to cause non-compliance.

Table 4.22. Radon flux results for bounding uncertainty cases.

Bounding Case	10,000 Year Flux (pCi m^{-2} s^{-1})	Maximum Flux (pCi m^{-2} s^{-1})
Case 2b	14	392
Case 2c	23	644
Case 3b	14	392
Case 3c	28	756

The bounding uncertainty cases for Pit 6 are also presented in Table 4.22 as cases 3b and 3c. The results are very similar to those obtained for shallow land burial, and similar conclusions can be drawn for the upper (low-level) waste cell. This is expected because the upper cell controls the radon flux. Therefore, the results for Pit 6 are insensitive to parameters for the special case waste in the lower cell. After the first 700 years, the only difference between Pit 6 and the shallow land burial problem is the thickness of the waste cell. The model has been shown to be relatively insensitive to waste cell thickness.

4.4 INTERPRETATION OF ANALYSIS RESULTS

4.4.1 Interpretation of Doses to Members of the General Public

To interpret the results presented in Section 4.1.1 for members of the general public, it is necessary to consider the conservative assumptions inherent in the underlying calculations and the sensitivities and uncertainties associated with these calculations. The following discussion reviews the conservative assumptions in the estimated release rates to the accessible environment and in the calculations of subsequent transport, exposure, and dose. The results are then interpreted in light of these conservative assumptions and the model sensitivities discussed above.

In Section 3.2.2, the models and equations describing the assumptions made to estimate rate of release of radionuclides from the waste to the near-field environment were presented. Four main pathways of release were identified in the conceptual model: (1) diffusion of volatile radionuclides through the soil cap, (2) root uptake of radionuclides from the waste to overlying soil, (3) transport of radionuclides as a result of soil excavation by burrowing

Conservative assumptions inherent in estimates of release rates characterizing these pathways are listed below.

- To evaluate the release of potentially volatile radionuclides, the entire inventories of ^{3}H and ^{14}C are assumed to be immediately available for diffusion, as HTO and $^{14}CO_2$ (Section 3.2.2.1).

- Diffusive flux is assumed proportional to the initial concentration of the volatile radionuclide, until the entire inventory is depleted. In reality, the driving force or concentration gradient, would decline as diffusion occurs.

- Exchange of ^{3}H or ^{14}C with hydrogen or carbon in the vadose zone during diffusion to the surface is neglected.

- To evaluate the release of non-volatile forms of ^{3}H and ^{14}C, the entire inventory of these radionuclides is assumed non-volatile.

- Five percent of the root biomass is assumed to penetrate to depths below 2.4 m. This is highly conservative, as evidence to date indicates most roots are within 1.5 m of the surface (Section 3.2.2.3).

- The annual amount of soil excavated by insects is maximized by conservatively assuming a 10-year colony lifetime and selecting an upper-limit value for the percentage of soil excavated from depths greater than 1.5 m.

Conservative assumptions inherent in estimates of dose from the release of radionuclides from the undisturbed site include:

- Transient visitors are assumed to spend up to 2,000 hours per year at the site.

- The neglect of shielding by structures in the transient occupancy scenario.

- The assumption that inhalation of suspended soils occurs continuously during the time of occupation (i.e, no indoor residency occurs).

- The use of a conservative estimate of the annual average mass loading parameter, M_s, of 10^{-4} g soil per m^{-3} of air.

- The lack of a correction for source area size in the mass loading equation, so the facility is assumed to have an infinite area.

- The use of conservative values for deposition velocity and foliar interception fraction.

- The open rangeland scenario assumes that the entire vegetable intake is produced at the offsite residence and that all milk and meat products consumed are produced in contaminated areas at the RWMS. It is extremely conservative to assume that all the beef and milk consumed is produced at the Area 5 RWMS. As much as 81 percent of the dose in the open rangeland scenario is due to consumption of milk. It is assumed that this milk is obtained entirely from cattle grazing on contaminated native vegetation at the RWMS. Dairy production on unirrigated Mohave Desert rangeland would be an extremely marginal activity. It is unlikely that the entire milk intake could be produced at the RWMS. Eliminating the milk pathway reduces the dose in the open rangeland scenario at 10,000 years to 0.03 mrem yr^{-1} and the maximum dose to 0.3 mrem yr^{-1}.

The model sensitivity results in Section 4.2.1 indicate that for ^{226}Ra, which contributes most of the dose in the transient occupancy scenario, and a large portion of the dose in the open rangeland scenario, the amount of contaminated soil brought to the surface by burrowing ants is the most important model parameter. However, since conservative parameters were selected to estimate the transfer rate, K_{b1}, it is not reasonable to assume a significantly larger value for this parameter than the one used in the base case.

Model sensitivity results for ^{14}C, a nuclide with a large soil-plant concentration factor, indicate that root uptake is the most sensitive parameter. The root uptake model is conservative, because it assumes five percent of the plant roots penetrate to a depth of 4.4 m. Site-specific data suggest that perennials native to the area rarely root below 2 m. The models adopted to evaluate doses, and the model sensitivity evaluation, reasonable assurance is provided that the RWMS facility will meet the performance objective for protection of members of the general public.

4.4.2 Interpretation of Radon Flux Results

The flux of ^{222}Rn from waste disposal cells at the Area 5 RWMS has been estimated considering its diffusive and advective transport in the air-filled pore space. The radon flux was estimated to be approximately 6 pCi m^{-2} s^{-1} at 10,000 years for both shallow land burial trenches and Pit 6 using best estimate parameters. These results were shown to be most sensitive to waste porosity and waste ^{226}Ra activity concentration. Bounding values for waste porosity and ^{226}Ra activity concentration were not sufficient to generate cases that exceed the 20 pCi m^{-2} s^{-1} flux limit at 10,000 years. These results suggest that waste streams currently being received at the Area 5 RWMS and disposed at a depth of 2.4 m are very close to the flux limit by 10,000 years. However, the final closure cap is very likely to be thicker than 2.4 m and the fluxes can be expected to be attenuated to below 20 pCi m^{-2} s^{-1}.

4.4.3 Interpretation of Doses to Inadvertent Intruders

Three intruder scenarios were evaluated for the Area 5 RWMS. A single acute or short-term scenario was considered, involving the exposure of a drilling intruder to contaminated cuttings. Two chronic scenarios, the intruder-agriculture and post-drilling scenarios, were evaluated. These assume full time occupation of the site and consumption of food produced in the contaminated zone. All three scenarios represent extremely unlikely events, especially for an arid unpopulated site such as the Area 5 RWMS.

The intruder scenarios have been analyzed primarily to set conservative waste concentration limits for various waste disposal options. The intruder performance objective is the limiting criterion in the near-term because natural release processes from the undisturbed site operate very slowly. Over thousands of years, the models of undisturbed site performance suggest that natural transport processes can cause certain long-lived radionuclides to accumulate in the shallow soils. However, soil concentrations and doses in the intruder-agriculture scenario still bound the results for the members of the public for the inventory below 2.4 m. For deeper source terms, natural release processes are expected to be reduced, and the post-drilling scenario is expected to be the bounding scenario.

Intruder scenarios represent an extremely conservative method of setting waste concentration limits. It is unlikely that these events will ever occur or that the projected doses will ever be realized. In addition, very conservative assumptions have been made including:

- The assumption that intrusion and chronic exposure can begin within 100 years after site closure. The arid conditions at the Area 5 RWMS will probably ensure that many of the waste forms present will remain intact and identifiable as refuse for many hundreds, if not thousands, of years. It is unlikely that an intruder would disperse refuse over an area that was intended to be used as a residence and ranch.

- The assumptions that the intruder spends 70 percent of their time on site, respires at the rate of 8,400 $m^3\ yr^{-1,}$ and is exposed to a dusting loading of 1.54×10^{-4} g m^{-3}. These are conservative values that contribute to the inhalation dose, which is a major route of exposure. The high occupancy factor also contributes to the external doses, which is the other major exposure pathway. The intruder's residence is assumed to transmit 70 percent of incident photons.

- The assumption that 25 percent of the intruder's entire diet consists of food produced in the contaminated zone. Although this is physically possible, it is unlikely that an individual would ever use such a small area this intensively. Furthermore, the extreme climate, deep groundwater resources, and poor soils at Area 5 would make most agricultural activities extremely expensive. However, ingestion is a minor pathway for most of the radionuclides disposed of at the Area 5 RWMS and these conservative assumptions have little impact on the total dose.

- All volatile radionuclides are assumed to be released at a maximum rate to a 2 m mixing zone and into the intruder's residence.

Conservative assumptions are made within the intruder scenarios to account for the great scenario uncertainty. Waste concentration limits derived from these conservative analyses will provide reasonable assurance of meeting the performance objectives.

Three acute intruder scenarios were evaluated in the performance assessment. Two, the discovery and intruder-construction scenarios, were eliminated because they are bounded by chronic exposure scenarios. The remaining scenario, the drilling scenario, involves exposure to soil with a significantly greater activity concentration than occurs in the subsequent chronic post-drilling scenario. Therefore, the drilling scenario was evaluated for comparison with the performance objectives. The total effective dose equivalent was estimated to be

0.15 mrem at 100 years and 0.17 mrem at 10,000 years for a driller penetrating a shallow land burial trench. The results for Pit 6 were 22 mrem at 100 year and 23 mrem at 10,000 years. The doses are significantly less the than the 500 mrem limit and provide reasonable assurance of compliance.

Three chronic intruder scenarios were considered in the performance assessment. The resident scenario was rejected as physically unreasonable for a site without stabilized waste forms. The two remaining scenarios, the intruder-agriculture and post-drilling scenarios, were analyzed and preliminary waste concentration limits were set based on the results.

The intruder-agriculture scenario describes the exposure of an onsite resident to soil contaminated with waste from a construction excavation. This scenario was analyzed to determine the concentration of wastes that could be disposed of below the current 2.4 m depth of burial. This scenario was analyzed for the shallow land burial inventory only. The total effective dose equivalent at 100 years was estimated to be 84 mrem yr^{-1}. At 10,000 years, the estimated doses increase to 157 mrem yr^{-1}. The increasing dose within 10,000 years is due almost entirely to production of ^{226}Ra from the decay of ^{238}U decay chain members. Under the current interpretation of the performance objectives, the shallow land burial inventory meets the 100 mrem yr^{-1} intruder dose limit at 100 years, but exceeds it at some time before 10,000 years. Since the activity concentration of the inventory analyzed in the performance assessment is equivalent to the concentration of waste disposed of from FY89 to FY93, waste has been disposed of that would not meet the concentration limits developed in Section 4.2.2. However, this conclusion should be considered in light of the conservative assumptions noted above and the extremely low doses estimated for the more realistic exposures to the general public described in Section 4.1. As will be shown below, the shallow land burial inventory does meet the concentration limits for wastes disposed of below 4 m. Therefore, this inventory can be brought into compliance with the current performance objectives by installing a final closure cap at least 4 m thick. It has been noted that proposed waste disposal performance objectives would limit the intruder analysis to intrusion occurring within a few hundred years of closure. Since the intruder-agriculture analysis fails due to ingrowth of ^{226}Ra occurring after thousands of years, the current inventory would probably meet the proposed revisions to USDOE Order 5820.2A. Therefore, no action would be required if these requirements are in place at the time of closure. Since closure is many years away, no action is required at this time.

The post-drilling scenario is similar to the intruder-agriculture scenario except that the volume of waste exhumed is less. As a consequence, the activity concentration and thickness of the contaminated zone is also less. This scenario is used to derive concentration limits for wastes disposed below the depth of common construction excavations or conservatively 4 m. The estimated TEDE for the shallow land burial inventory was 0.70 mrem yr^{-1} at 100 years and 0.71 mrem yr^{-1} at 10,000 years. The predicted doses are well below the performance objective throughout the 10,000-year compliance period. However, if the lower cell of Pit 6 is assumed to be filled with special case thorium waste, the performance objective cannot be meet. The predicted total effective dose equivalent for Pit 6 filled with special case thorium waste was 163 mrem yr^{-1} at 100 years and increases slightly to 178 mrem yr^{-1} at 10,000 years. The radon flux analysis in Section 4.1.4 indicated that increasing the depth of burial effectively eliminates the radon release problem. The thorium waste streams fail the post-drilling intruder analysis because of external irradiation from ^{228}Th+D and ^{228}Ra+D and lesser contributions from inhalation of ^{232}Th+D.

The results presented above assume an activity concentration for the thorium waste stream that is equivalent to materials disposed of from FY89 to FY93. As of the end of FY93, 18 Ci of ^{232}Th had been received for disposal in Pit 6. Mean activity concentration limits for Pit 6 have been presented in Table 4.16. An inventory limit can be set as the product of the activity concentration and waste cell volume (5,600 m^3). This leads to a total inventory limit for the lower cell of Pit 6 of 174 Ci of ^{232}Th. Preliminary estimates of the total ^{232}Th inventory at the Fernald Environmental Management Project indicate the inventory is significantly less than the 174 Ci limit and that this inventory can be placed in Pit 6. Compliance with the performance objectives for Pit 6 can be assured by implementing a ^{232}Th inventory limit for the lower cell.

The dose to an intruder from inhalation of short-lived progeny of radon was estimated in Section 4.4.4. These analyses showed that the dose from radon released from the buried waste zone far surpasses the dose from the contaminated zone on the surface. Therefore, a single analysis is applicable to all intruder scenarios. The results of the analyses indicate that reasonable protection is provided out to 10,000 years, when at least 4 m of cap is present for attenuation of the fluxes. The NCRP has estimated that an average individual receives approximately 200 mrem yr^{-1} from background exposure to radon (NCRP, 1987). Since background soil concentrations of ^{226}Ra at the NTS (1.2 pCi g^{-1}) are approximately double average background concentrations, background ^{222}Rn doses to an intruder at Area 5 could be as high as 400 mrem yr^{-1}. With a 4 m cap present, the highest CEDE from buried waste was 107 mrem yr^{-1}, approximately one fourth of the annual background exposure. Since doses from radon represent a fractional increase over natural background levels, compliance with the radon flux standard can be considered to be protective for inadvertent intruders.

5.0 PERFORMANCE EVALUATION

A performance assessment is the systematic analysis of the risks posed by a waste management system to the general public and the environment, and a comparison of those risks to the performance objectives. This section summarizes the results of the performance assessment presented in the previous sections and compares those results with the performance objectives. Additionally, the implications of the performance assessment for site characterization, site monitoring, waste operations, and future performance assessments are interpreted.

5.1 COMPARISON OF PERFORMANCE ASSESSMENT RESULTS WITH THE PERFORMANCE OBJECTIVES

This performance assessment assesses the risk to two populations. The risk to the general public has been assessed through the analysis of several reasonable, yet conservative, scenarios that reflect site-specific conditions at the Area 5 RWMS. The risk to hypothetical

Exposures through airborne pathways were also extremely low. The greatest TEDE from exposure to airborne radioactivity, excluding radon, was 0.2 mrem yr^{-1}. Radon emissions were estimated to remain below 6 pCi m^{-2} s^{-1} for 10,000 years after closure.

Table 5.1. Performance assessment results for members of the general public.

Performance Objective	Performance Assessment Result	Conclusion
25 mrem yr^{-1} from All Pathways	0.6 mrem yr^{-1}	Complies
10 mrem yr^{-1} from Airborne Emissions Excluding Radon	0.2 mrem yr^{-1}	Complies
Average Annual ^{222}Rn Flux Less Than 20 pCi m^{-2} s^{-1}	6 pCi m^{-2} s^{-1}	Complies
Protect Groundwater Resources	Zero Release to Aquifer in 10,000 Years	Complies

Protection of groundwater resources are ensured by the natural properties of the disposal site rather than the performance of engineered barriers or stabilized waste forms. Site characterization studies have demonstrated that the vadose zone is approximately 235 m thick and that the water potential gradient is upward in the upper 35 m. Water in the upper 35 m of the alluvium tends to move upward rather than downward to the aquifer. Although there is a potential for upward migration, upward advection and diffusion is rendered negligible by the extremely dry conditions. A modeling study of transient conditions in the vadose zone suggests that infiltrating precipitation does not affect the water content and water potential profile below a depth of about 0.25 m. Therefore, the zone where waste is placed is burial inventory was found to be in compliance with the performance objectives when analyzed in the post-drilling scenario, but exceeded the limit when analyzed in the intruder-agriculture scenario. The intruder-agriculture scenario assumes an intruder constructs a residence over the site and resides within a contaminated zone created during the construction of the residence. The shallow land burial inventory meets the performance objective when analyzed in the intruder-agriculture at 100 years, but eventually fails, as ^{226}Ra is produced by radioactive decay of ^{238}U chain members. However, increasing the thickness of the closure cap from 2.4 m to 4.0 m, thereby eliminating the possibility of a construction excavation reaching the buried waste, ensures compliance.

The inventory assumed for Pit 6 was found to exceed the performance objective when analyzed in the post-drilling scenario. This analysis used an estimated mean activity concentration based on wastes received from FY89 to FY93. The analysis results exceeded the performance objective because of the ^{232}Th concentration assumed for the lower cell. The ^{232}Th inventory limit set for Pit 6, 174 Ci, greatly exceeds the activity disposed of to date, which is 18 Ci. Therefore, compliance with the performance objectives can be assured by implementation of an inventory limit or activity concentration limit. Preliminary information indicates that the entire inventory of Th waste at the Fernald Environmental Management Project is less than the 174 Ci limit set for Pit 6.

Table 5.2. Performance assessment results for intruder scenarios. Results are based on current waste management practices. Conclusions regarding compliance are based on implementation of corrective actions.

Performance Objective	Performance Assessment Result		Conclusion
	Shallow Land Burial	Pit 6 (PO6U)	
500 mrem Acute Scenario Drilling	0.2 mrem	23 mrem	Complies/Complies
100 mrem Chronic Scenario Agriculture Post-Drilling	 157 mrem yr^{-1} 0.7 mrem yr^{-1}	 Not Applicable 178 mrem yr^{-1}	 Complies† Complies/Complies‡

† Assumes installation of 4 m cap at closure.

‡ Assumes implementation of waste concentration limit or inventory limit.

5.2 APPLICATION OF PERFORMANCE ASSESSMENT RESULTS TO THE DEVELOPMENT OF WASTE ACCEPTANCE CRITERIA

The results of the performance assessment indicate that the chronic intruder performance objective and radon flux performance objective are the limiting standards. Concentration limits based on intruder and radon flux analyses have been developed in the previous chapter. These limits can be used with other information to develop formal concentration limits to be included in the site waste acceptance criteria.

The final waste acceptance criteria should be a waste package activity concentration limit, in units of activity per unit volume. The concentration limits should be the limiting value obtained from performance assessment results, operational safety analysis results, U.S. Department of Transportation shipping requirements, USNRC Class C limit values, and any other pertinent standard. Generator reporting and characterization requirements should be based on the concentration limits. It is recommended that a screening level be set below the concentration limit. Waste characterization should be more rigorous for proposed waste streams exceeding the screening limit.

The waste acceptance criteria described above use a concentration limit that is applied to each waste package. Compliance with the performance objectives can be assured if the mean concentration in a disposal unit meets the requirements. It is possible to allow individual packages to exceed the concentration limits as long as the mean concentration within the disposal unit is below the limit. Therefore, the waste acceptance criteria should not be viewed as absolute limits. Each package exceeding the concentration limit requires a recalculation of the concentration limit for packages disposed of later. This will cause each disposal unit to have its own waste acceptance criteria and the criteria may change over time. This creates potential operational difficulties that should be carefully evaluated.

The performance assessment describes several sets of waste concentration limits based on differing waste disposal options. These limits could be used to develop a waste classification system. Segregation of waste according to activity concentration may offer cost savings if sufficient volumes of the classes are available for disposal. The disposal of higher activity waste may be more costly due to depth of burial or stabilization requirements. Minimizing the volume of these wastes by segregation may reduce disposal costs.

5.3 RECOMMENDED MODIFICATIONS TO OPERATING PROCEDURES

This section summarizes recommended changes to waste management operating procedures. The recommendations are expected to either decrease the uncertainty in performance assessment results or to improve long-term site performance. The major source of uncertainty in the performance assessment is uncertainty in the source term. Most of the recommended improvements deal with waste characterization and record keeping related to waste characterization.

1. Make radionuclide reporting requirements for waste generator applications consistent with reporting requirements for final disposal (Form RE-0166) to the maximum extent possible.

   Discussion: Radionuclide reporting requirements for generator applications and final disposal are not consistent. There are inconsistencies in the nuclides that must be reported, activity concentration units and information reported that describes the waste stream. Waste characterization data reported in the application and at the time of disposal are used for essentially the same purpose: to determine compliance with the

Discussion: Disposal records were reviewed during preparation of the performance assessment. Discrepancies were found in the way short-lived progeny were reported. These discrepancies affect the uncertainty in the performance assessment results. For long-lived progeny that, in turn, decay to other long-lived radioactive progeny, the activity initially present at disposal can have a significant effect on activity present in the future. Consistent reporting guidelines should be developed. A short list, less than a page in length, could be developed that would eliminate this problem.

4. Require generators to report the activity concentration of all isotopes of uranium that exceed one percent of the total activity concentration of the waste stream.

   Discussion: During preparation of the performance assessment it was determined that generators are not correctly reporting uranium isotopes. There are three naturally occurring isotopes of uranium, ^{238}U, ^{235}U, and ^{234}U. All uranium-bearing waste streams will contain these isotopes. Most generators are reporting a single isotope, ^{238}U for depleted uranium and ^{235}U for enriched uranium. For example, generators have reported that 21 Ci of ^{234}U was sent to the Area 5 RWMS from FY89 to FY93. Review of generator waste streams suggest that an additional 48 Ci of unreported ^{234}U was probably present. This additional ^{234}U activity significantly affected the performance assessment results by increasing the inventory of ^{226}Ra present at 10,000 years. Most of the ^{226}Ra in the Area 5 RWMS inventory at 10,000 years is produced by the decay of ^{234}U. Radium-226 and its short-lived progeny, ^{222}Rn, were found to be a major contributors to dose in the performance assessment.

5. Review approved waste streams to confirm that they meet preliminary waste acceptance criteria.

   Discussion: Several of the preliminary concentration limits developed for ^{234}U in the performance assessment are close to the mean ^{234}U activity concentration in waste disposed of from FY89 to FY93, 5.4×10^{-3} Ci m^{-3}. Since all waste streams do not contain ^{234}U at the average activity concentration, it seems very likely that there are approved waste streams that exceed the limit for ^{234}U. The same result was obtained for the thorium wastes streams destined for Pit 6. It is recommended that all approved waste streams be reviewed to determine if they are likely to meet the waste concentration limits. Waste streams exceeding package concentration limits do not necessary have to be rejected. Instead, more complex inventory limits would have to be set for pits and trenches receiving these wastes.

6. Develop a formal procedure to identify potential special case wastes that may not meet the waste acceptance criteria before the waste are transferred to the NTS. Develop a program to identify risk assessment approaches or waste disposal operations that can be used to provide reasonable assurance that special case wastes can meet the performance objectives.

   Discussion: It is recommended that a screening concentration be adopted that is a fraction of the waste concentration limits. Waste below this concentration should be routinely accepted. Waste above this limit should receive special consideration regarding waste characterization, waste stabilization, waste packaging, waste placement in the disposal site and design, and closure of waste disposal units.

7. Require generators to identify inherently stable or stabilized waste forms so that credit can be taken in performance assessment.

   Discussion: This performance assessment takes no credit for waste form, because the inventory of stabilized waste forms cannot be determined from database records. It is recommended that generators be required to report whether waste streams are stabilized at the time of application and, if so, to report the stabilization method. This information would be useful in future performance assessments.

5.4 CONTINUING WORK FOR SITE CHARACTERIZATION, SITE MONITORING PROGRAMS, AND FUTURE PERFORMANCE ASSESSMENTS

Performance assessment results can guide site characterization, site monitoring, and future assessment activities. All release mechanisms identified in this performance assessment involve upward transport. An increased understanding of the hydrologic and biologic processes operating in the near-surface will reduce uncertainty in performance assessment models and increase confidence in the selected depth of burial.

The performance assessment assumes that there is no upward advection and diffusion based on the dry ambient water content of the near-surface alluvium and modeling results suggesting that infiltrating water does not penetrate to the depth of buried waste. The transient infiltration modeling was based on preliminary evapotranspiration data collected from lysimeter and micrometeorology experiments. These experiments should be continued to increase confidence in performance assessment results and to develop data that may be used to validate unsaturated transport codes. The results of the performance assessment are strongly dependant on the conclusion that transport to the aquifer is not occurring. The lysimeter and micrometerology experiments provide additional evidence supporting the conclusion that recharge is negligible and will bolster performance assessment results.

The sensitivity analysis of the radionuclide release model indicated that the model was most sensitive to the quantity of buried waste excavated by invertebrates for nuclides with low plant-soil concentration factors. For nuclides with high plant-soil concentration ratios, model results were found to be most sensitive to uptake by plants with roots in the buried waste. Relatively little site-specific data are available concerning the ability of insect or plants to transport materials to the surface from the depth of burial. Uncertainty could be reduced with additional data on the population densities, excavation rates, and the depth distribution of invertebrate burrows in Frenchman Flat. No site-specific data were identified concerning invertebrate burrowing. Reliable data on the rooting depth of native perennial plants in Frenchman Flat should be collected. Site-specific studies reported to date are, in all cases, anecdotal. More rigorous investigations of native and introduced plant rooting depth are worthy of consideration. Productivity of native floral communities has been studied and reported for many years at several plots within Frenchman Flat and Rock Valley. Plant beta, and gross alpha, and gross beta. Vadose zone monitoring offers an earlier indication of release and is preferred to groundwater monitoring.

6.0 PREPARERS

Gregory J. Shott

M.S. University of Washington, Ocean and Fishery Science - 1984.

B.S. University of New Hampshire, Biology - 1981.

Gregory J. Shott is a Certified Health Physicist (CHP) pursuing an M.S. in health physics from the Georgia Institute of Technology. He has completed two years of graduate study at the Laboratory of Radiation Ecology, University of Washington and has nine years of experience in environmental monitoring and waste management. Gregory Shott acted as the project manager and completed the intruder pathway analysis.

Curtis J. Muller

M.S. Hydrology - University of Arizona - 1992.

B.S. Geological Engineering - Michigan Technological University - 1982.

Currently working for REECo as a Waste Management Specialist, Curtis has extensive earth science training and experience as both a geophysicist (Atlantic Richfield Corp, Dallas TX) and hydrologist. Curtis also has additional training in radioactive waste management technology and is contributing to vadose zone hydrology and modeling at the NTS. Curtis Muller produced all sections related to the site geology and hydrologic modeling, as well as numerous graphics and tables throughout the text.

Lawrence E. Barker

Ph.D. Statistics - Florida State University - 1979.
M.S. Statistics - Florida State University - 1976.
B.S. Mathematics - University of Kentucky - 1975.

Mathematics at the University of Tennessee for five years. His work has recently appeared in *Soil Science Society American Journal*, as well as numerous DOE publications. Lawrence Barker acted as a technical consultant and editor for the performance assessment.

David E. Cawlfield

B.S. Chemistry - Oregon State University - 1969.

David Cawlfield has extensive knowledge and experience as a software/analyst - systems engineer specializing in scientific and engineering applications including

Deron G. Linkenheil

M.S. Ecological Engineering - Colorado School of Mines - 1993.
M.S. Health Physics and Radioecology - Colorado State University - 1990.
B.S. Biological Sciences - Colorado State University - 1988.

Deron Linkenheil currently works for REECo as a Waste Management Specialist. His responsibilities include all aspects of the waste management program and serving on several DOE Committees. Deron worked as a Health Physicist approximately four years for EG&G Rocky Flats, Inc., developing all phases of the radiation protection program, and was the principal health physicist for several large remediation projects involving plutonium. Deron Linkenheil prepared the site inventory.

Laura McDowell-Boyer

Ph.D. Civil/Environmental Engineering.
M.S. Radiological Health Physics.

Laura McDowell-Boyer has nine years experience in radiological exposure assessment and transport modeling. She has directed the development of a multimedia environmental transport model for chemicals, studied mechanisms of subsurface contaminant migration, and modeled flow and transport. She has coordinated two LLW waste performance assessments for other sites. Laura McDowell-Boyer performed the analysis of doses to the general public.

Michael J. Sully

Ph.D. Soil Science - University of California, Davis - 1984.
M.S. Atmospheric Science - University of California, Davis - 1979.
B.A. Physics - University of Montana, Missoula - 1976.

Michael Sully is the principal hydrologist in charge of the site characterization of flow, transport properties, and field investigation of soil-plant-water interactions for REECo. He has served as an assistant professor at the Department of Hydrology and Water Resources at the University of Arizona, and as an experimental scientist at CSIRO Division of Environmental Mechanics in Canberra, Australia. He has submitted numerous research articles for both national and international publications.

Michael Sully acted as a technical consultant on issues related to soil physics and vadose zone hydrology.

David J. Thorne

M.S. Radiological Heath Physics.
B.S. Geology.

David Thorne has seven years experience in radiological transport and dose assessments. His experience includes source term development, contaminant transport modeling, dose and risk assessment, and environmental compliance. David Thorne assisted Laura McDowell-Boyer in the preparation of analyses of doses to members of the general public.

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APPENDIX A

WASTE ACCEPTANCE CRITERIA STATEMENTS
(As received)

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5.5 Waste Acceptance Criteria Statements

Address each of the following waste acceptance criteria (WAC). Provide a brief statement of the NVO-325 criteria objective. State the regulatory or other reference(s) as provided in the WAC and provide a brief discussion of how each waste stream will comply with the individual criteria. In addition, where compliance is procedurally controlled, reference the applicable procedure(s). For example:

1) **Closure:** The package closure shall be sturdy enough that it will not be breached under normal handling conditions and will not serve as a weak point for package failure (per NVO-325, 5.5.1.3.A).

   Compliance Method: Waste containers shall be closed with metal clips and banding, per procedure XXXX, to prevent breaching under normal handling conditions.

2) **Free Liquids:** LLW disposed at the NTS waste management sites shall contain as little free liquids as is reasonably achievable, but in no case shall the liquid equal or exceed 0.5 percent by volume of the external waste container (per NVO-325, 5.5.1.1.C).

   Compliance Method: This criteria is evaluated by process knowledge, waste segregation, visual verification, and evaluation of the waste stream (e.g., contaminated soil) utilizing the Paint Filter Test, per procedure XXXX, XXXX, and XXXX. Absorbent will be added, per procedure XXXX, as a precautionary measure to absorb any moisture that may form due to condensation attributed to the variations in temperature and humidity from state-of-generation to NTS. Packages will also be reviewed by Real-Time Radiography (RTR) prior to package certification. Any packages suspected of having greater that 0.5 percent free liquids will be segregated and marked to prevent inadvertent shipment to NTS.

5.5.1 Low-level Waste Acceptance Criteria

Defense waste accepted at NTS must be radioactive and meet the waste form criteria outlined below. These requirements are minimum requirements for all types of wastes and are intended to facilitate handling and provide health and safety protection of personnel at the disposal site.

5.5.1.1 General Waste Form Criteria

These waste form criteria are based on current DOE LLW management policies and practices per DOE Order 5820.2A guidelines. Any waste streams not meeting these basic requirements must be evaluated on a case-by-case basis and must not compromise the performance objectives for the disposal site or violate any permit requirements.

A. **Transuranics:** LLW must have a transuranic nuclide concentration less than 100 nCi/g. The mass of the waste container, including shielding, shall not be used in calculating the specific activity of the waste.

B. **Hazardous Waste Components:** LLW offered for disposal at NTS waste management sites shall not exhibit any characteristics of, or be listed as, hazardous waste as identified in Title 40 CFR 261, "Identification and Listing of Hazardous Waste" or state-of-generation hazardous waste regulations.

C. **Free Liquids:** Free liquids mean liquids which readily separate from the solid portion of a waste under ambient temperature and pressure conditions.

   LLW disposed at the NTS waste management sites shall contain as little free liquids as is reasonably achievable, but in no case shall the liquid equal or exceed 0.5 percent by volume of the external waste container and shall meet the following criteria:

   - Bottles, cans, or other similar well-drained containers may contain residual liquids.
   - Where practicable, residual liquids in well-drained containers shall be mixed with absorbent or solidified so that free liquids are no longer observed.

- If absorbent materials are added to a waste for control of free liquids, the generator must calculate the volume of liquid in the waste and use a quantity of sorbent material sufficient to absorb a minimum of twice the calculated volume of the liquid. Please note when significant differences of temperature exist between the generating site and the disposing site, provisions for additional absorbent materials must be made for affected waste forms.
- To demonstrate compliance with the free liquids requirement, the generator may be required to use Method 9095 (Paint Filter Test) as described in "Test Methods For Evaluating Solid Wastes, Physical/Chemical Methods." (EPA Publication No. SW-846) The Paint Filter Test may not be applicable to certain waste forms; e.g., concrete. If the generator determines that the waste form is not conducive to the Paint Filter Test, documentation must be provided to substantiate the claim.

D. Particulates: Fine particulate wastes shall be immobilized so that the waste package contains no more than 1 weight percent of less-than-10-micrometer-diameter particles, or 15 weight percent of less-than-200-micrometer-diameter particles. Waste that is known to be in a particulate form or in a form that could mechanically or chemically be transformed to a particulate during handling and interim storage shall be immobilized.

When immobilization is impractical, other acceptable waste packaging shall be used, such as the following:

- Overpacking (i.e., 55-gallon drum inside 83- or 85-gallon drum);
- steel box with no liner;
- wooden box with a minimum of 6-mil sealed plastic liner;
- steel drum with a minimum of 6-mil sealed plastic liner.

E. Gases: LLW gases shall be stabilized or absorbed so that pressure in the waste package does not exceed 1.5 atmospheres at 20° C.

Compressed gases as defined by Title 49, CFR 173.300, including unpunctured aerosol cans, will not be accepted for storage or disposal. Aerosol cans will have puncture disfigurements recognizable by (RTR). Expended gas cylinders must have the valve mechanism removed.

F. **Stabilization:** Where practical, waste shall be treated to reduce volume, promote waste minimization, and provide a more structurally and chemically stable waste form.

Structural stability can be accomplished by crushing, shredding, and placing a smaller piece inside an opening of a larger piece, such as nesting pipes.

Chemical stability must be documented to show that significant quantities of harmful gases, vapors, or liquids are not generated. Wastes shall not react with the packaging during storage, shipping, and handling time.

Where stabilization is required for the waste to meet this waste acceptance criteria, it must be shown that the stabilization process is adequately controlled. Control is shown through the use of procedures, sampling, test plans, etc., and the results of such controls shall be made available for examination and approval.

G. **Etiologic Agents:** LLW containing pathogens, infectious wastes, or other etiologic agents as defined in Title 49, CFR 173.386 will not be accepted for disposal at NTS.

H. **Chelating Agents:** LLW containing chelating or complexing agents at concentrations greater than 1 percent by weight of the waste form will not be accepted.

I. **Polychlorinated Biphenyls (PCBs):** PCB-contaminated LLW will not be accepted for disposal at NTS unless the PCB concentration meets municipal solid waste disposal levels of 50 ppm or less. See Title 40, CFR 761.60 for PCB disposal requirements.

Waste Stream Information

C. Nuclear Heating: The quantity of radioactive materials shall be limited for each waste matrix and package type so that the effects of nuclear decay heat will not adversely affect the physical or chemical stability of the contents or package integrity. See Title 49 CFR 173.442, "Thermal Limitations," for temperature limits of accessible external package surfaces.

D. Radiation Levels: The external radiation levels for packages shall not exceed 200 millirem per hour on contact during handling, shipment, and disposal unless specifically excepted by DOT regulations. See Title 49 CFR 173.441, "Radiation Level Limitations." Type B containers that will be unloaded by remote procedures will be addressed on a case-by-case basis.

E. External Contamination: Packages shall be within DOT contamination limits upon receipt at NTS. See Title 49 CFR 173.443, "Contamination Control." On-site generators refer to current NTS external contamination limits.

F. Activity Limits: The activity limits listed in Title 49 CFR 173.431, "Activity Limits for Type A and Type B Packages," shall be met. Where applicable, the activity limits of Titles 49 CFR 173.421, "Limited Quantities of Radioactive Materials," and 49 CFR 173.425, "T [illegible] Requirements for Low-Specific Activity Radioactive Materials," shall be met for strong, tight packages. See Section 5.5.5.2 for additional requirements for activity limits outside of this range.

G. Multiple Hazards: Waste containing multiple hazards shall be essential to reducing the number of waste shipments to the NTS and the space required for disposal. DOE/NV has adopted the following criteria to assure that the NTS RWMSs are operated safely and efficiently. The criteria shall be incorporated in the design of all waste packaging, including strong, tight containers.

A. **Closure:** The package closure shall be sturdy enough that it will not be breached under normal handling conditions and will not serve as a weak point for package failure.

B. **Strength:** Except for bulk waste, waste packaged in steel drums or SEALAND® containers, the waste package (packaging and contents) shall be capable of supporting a uniformly distributed load of 19,528 kg/m2 (4,000 lbs/ft2). This is required to support other waste packages and earth cover without crushing during stacking and covering operations.

C. **Handling:** All waste packages shall be provided with permanently attached skids, cleats, offsets, rings, handles, or other auxiliary lifting devices to allow handling by means of forklifts, cranes, or similar handling equipment. Lifting rings and other auxiliary lifting devices on the package are permissible, provided they are recessed, offset, or hinged in a manner that does not inhibit stacking the packages. The lifting devices must be designed to a 5:1 safety factor based on the ultimate strength of the material. All rigging devices that are not permanently attached to the waste package must have a current load test based on 125 percent of the safe working load.

D. **Size:** 1.2- x 1.2- x 2.1-m (4- x 4- x 7-ft) or 1.2- x 0.6- x 2.1-m (4- x 2- x 7-ft) (width, height, length) boxes or 208-liter (55-gallon) drums are required to be used. Bulk waste container approval is discussed in Section 5.5.4. While these sizes allow optimum stacking efficiency in disposal cells, other dimensions are acceptable with approval from DOE/NV on a case-by-case basis.

E. Weight: In addition to the weight limits set for specific packaging designs, NTS imposes limits of 4,082 kg (9,000 pounds) per box and 544 kg (1,200 pounds) per 208-liter (55-gallon) drum. Packages exceeding 4,082 kg (9,000 pounds) require crane or large forklift

removal and must be approved by REECo/WMD prior to shipment. Shipments of this type must be in a removable-top or removable-side trailer.

F. Loading: Waste packages shall be loaded to ensure that the interior volume is as efficiently and compactly loaded as practical. High density loading will allow efficient RWMS space utilization and provide a more stable waste form that will reduce subsidence and enhance the long-term performance of the disposal site.

G. Nonstandard Type A Packaging: Use of DOT Type A packages not previously evaluated under the DOE Type A Package Certification Program (see MLM- 3245, etc.) will not be permitted.

H. Package Protection: The generator shall take the following precautions to protect the waste package after closure.

1. The preshipment storage environment shall be controlled to avoid adverse influence from weather or other factors on the containment capability of the waste packaging during handling, storage, and transport. The generator preparing waste for

I. **Marking and Labeling:** Each waste package shall have the following information:

1. Marking and labeling as required in Title 49 CFR 172, subparts D and E.
2. Signed NV-211 "Packaging Certification" label (revision date January 27, 1989) (see Figure 8, page 76). If the waste is unpackaged bulk, a signed NV-211 label must accompany the shipment papers. These labels can be obtained from REECo/WMD.
3. Shipment number in the following sequence: Two alpha character generator-site-designator codes assigned by WMD (see Appendix D); one alpha character for type of waste L for LLW, M for MW, T for TRU, or X for TRUMW; two numerical characters for current fiscal year; three numerical characters for shipment sequence. Example: MDL90001 would mean a shipment from EG&G Mound of LLW in fiscal year 1990 and the first shipment.
4. Package number shall be six characters (alpha, numeric, or combination) with no duplication within that shipment.
5. Approved 13-digit waste stream identification number (see Section 5.1).
6. Package weight in units of pounds and kilograms.

Note: Except for the required DOT labels and NV-211, these items *must be clearly and legibly placed on the container using* alphanumeric characters of at least one-half inch in height. The information that is included on the barcode label (see next section) does not need to be duplicated.

J. **Barcoding:** The shipment, package, and waste stream identification numbers shall be barcoded according to the following standards:

1. Code 39.
2. Medium to high density, high density preferred.

3. 1.0" high barcode.
4. Human readable interpretation (HRI) 0.50" high printed below the barcode.
5. Spacing between barcode and HRI will be 0.10".
6. Minimum left and right margin (quiet zones) will be at least 0.25".
7. All barcodes and HRI will be stacked with a minimum separation of 0.50" and in the following order: shipment number, container number, and waste stream identification number. (See Figures 6A and 6B.)

Note: Waste Stream ID number will not have the dash barcoded. EXAMPLE: LRY5-000000001 would be barcoded as LRY5000000001.

8. A total of two barcode labels shall be placed on each box or nonstandard package near the top and on opposite sides. Drums will have a total of two barcode labels, one on top of the drum lid and one on the side near the top.
9. A sample barcode must be submitted to WMD prior to the first shipment to ensure that WMD equipment can be used to read the barcode. WMD will provide barcodes if you are a low-volume generator (less than 10 shipments per year) and do not have the equipment to print barcodes. Contact WMD at least one month in advance to arrange for the barcodes.

K. On-Site Transfer: On-site transfer must be in accordance with NV 54XG.1A, NV Radiological Safety Manual, and applicable DOT requirements. For the transfer of unpackaged bulk material having external contamination, that contamination shall be fixed, covered, or contained sufficiently for safe transfer.

Figure 6A Barcode Label

Figure 6B Barcode Label

A5L92Ø01

ØØØØØ1

LRY1ØØØØØØØØ1

MINIMUM REQUIREMENTS FOR MEDIUM DENSITY BARCODE LABEL

5.5.2 Additional Criteria for Mixed Waste

In addition to meeting all of the LLW WAC, MW offered for disposal at the Area 5 RWMS Mixed Waste Management Unit (MWMU) must meet the criteria described below.

> **Note:** MW will not be accepted for bulk disposal in the Area 3 RWMS. MW containing asbestos will be handled on a case-by-case basis. State-of-generation requirements for identifying, treatment, and disposal will also apply.

A. Free Liquids: MW disposed at the NTS shall contain no free liquids.

- Residual liquids in well-drained containers shall be mixed with absorbent or solidified so that free liquids are no longer observed.
- If absorbent materials are added to a waste for control of free liquids, the generator must calculate the volume of liquid in the waste and use a quantity of sorbent material sufficient to absorb a minimum of twice the calculated volume of the liquid. Please note when significant differences of temperature exist between the generating site and the disposing site, provisions for additional absorbent materials must be made for affected waste forms.
- To demonstrate the absence of free liquids, the generator may be required to use Method 9095 (Paint Filter Test) as described in "Test Methods For Evaluating Solid Wastes, Physical/Chemical Methods." (EPA Publication No. SW-846) The Paint Filter Test may not be applicable to certain waste forms; e.g., concrete. If the generator determines that the waste form is not conducive to the Paint Filter Test, documentation must be provided to substantiate the claim.

Waste Stream Information

B. Treatment: All MW accepted for disposal at the MWMU must comply will be required to provide documentation with their application that the waste is certified to the WIPP WAC.

5.5.4 Additional Criteria for Bulk Waste

Bulk waste is disposed of in Area 3. It generally exists in a form not suited to the conventional packaging requirements of Area 5. In addition to meeting the LLW WAC, bulk LLW must meet the requirements of Title 49 CFR 173.425(c). NTS-generated bulk waste must be transported in accordance with NV 54XG.1A, "DOE/NV Radiological Safety Manual," and applicable DOT requirements.

Bulk waste containers must be approved by DOE/NV. Bulk waste containers may be returned to the generator after decontamination to meet NV 54XG.1A,

5.5.5.3 Radioactively Contaminated Asbestos

All regulated asbestos that is friable or otherwise capable of giving off friable asbestos dust must be wetted with a water and surfactant mix and stored in two plastic bags whose combined thickness equals at least 6 mil. The plastic bags must be overpacked in a leak-resistant wood or metal container that meets applicable shipping requirements for the radioactive content of the package involved. Sharp edges and corners within the package shall be padded or otherwise protected to prevent damage to the plastic inner wrap during handling, shipping, and disposal. Because the asbestos must be wetted during abatement activities, an absorbent must be added to ensure compliance with the free liquid requirement for LLW, see Section 5.5.1.1.C.

For further reference on regulated asbestos, see 40 CFR 61.140-61.157 and state-of-generation regulations. All LLW containing regulated asbestos shall be packaged, marked, and labeled in accordance with the requirements of 40 CFR 61.150.

> **Note:** Any regulated asbestos waste must be segregated into a separate waste stream.

SEALAND® containers are accepted on a case-by-case basis.

5.5.5.4 DOE Comparable Greater-Than-Class-C as Defined in 10 CFR 61.55

Disposal systems for such waste must be justified by a site-specific performance assessment through the National Environment Policy Act (NEPA) process and with the concurrence of EM-32 for all EM-1 disposal facilities and of NE-20 for those disposal facilities under the cognizance of NE-1.

Disposition of waste designated as greater-than-class-C, as defined in Title 10 CFR 61.55, will be handled as special case waste. Greater-than-class-C waste will be considered for disposal on a case-by-case basis depending on existing site-specific waste classification limits or limits that may be developed based on performance assessments.

APPENDIX B

SUPPLEMENTAL GEOLOGICAL INFORMATION

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General Stratigraphy Beneath the NTS

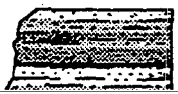
The stratigraphy beneath the NTS can be broadly classified, based on a hydrologic framework, into eight primary units with associated lithologic character as diagramed in Figure B.1 (Winograd and Thordarson, 1975). Figure B.1 is a highly idealized conceptual perspective of a very complex region. Because of erosion and structural deformation, the complete stratigraphic section does not exist within the NTS. This is apparent from a visual inspection of a surficial geological map of the area.

The stratigraphic units were deposited over long periods of geologic time under varying depositional environments. The lithologies range from clastic rocks and carbonate rocks in the bottom sections to volcanic clastic deposits of ash-fall and ash-flow tuff, rhyolites, and basalts in the upper sections. The topmost unit on which the Area 5 RWMS is located consists of unconsolidated valley fill alluvium. These units are described below from bottom to top, oldest to youngest.

Lower Clastic Rocks

The lowermost strata, beneath the NTS and above the crystalline basement rock, was the result of Precambrian deposition. These deposits derived from erosion off the craton into the shallow-water marine environment nearby. A subsiding miogeosyncline on the western edge of the North American continental margin produced a convenient depression for the accumulation of these sediments. These early erosional deposits have been classified into

GEOLOGICAL TIME SEQUENCE AT THE NEVADA TEST SITE

AGE*	ERA	PERIOD	EPOCH	DOMINANT CHARACTER	FORMATION NAME	STRATIGRAPHY‡
.01		QUATERNA	HOLOCENE	ALLUVIAL VALLEY FILL	ALLUVIAL VALLEY FILL: Alluvial fan, fluvial, lakebed, and mudflow deposits.	
4			PLEISTOCENE			

AGE[†]	ERA	PERIOD	EPOCH	DOMINANT CHARACTER	FORMATION NAME
	CENOZOIC	TERTIARY	MIOCENE	ASH-FLOW AND ASH-FALL TUFF	TUFF OF CRATER FLAT: Ash-flow tuff massively altered to clay and zeolites.
30			OLIGOCENE		ROCKS OF PAVITS SPRING: Tuffaceous sandstone, siltstone,
					HORSE SPRING FORMATION: Fresh-water limestone, conglomerate and tuff.
67	MESOZOIC	CRETACEOUS	LATE EARLY	GRANITE STOCKS	GRANITIC STOCKS: Granodiorite and quartz monzonite.
245	PALEOZOIC	PERMIAN	LATE	UPPER CARBONATE	TIPPIPAH LIMESTONE: Limestone.
		DEVONIAN	LATE	UPPER CLASTICS	ELEANA FORMATION: Argillite, limestone, conglomerate, and quartz.
360				LOWER CARBONATE	DEVILS GATE LIMESTONE: Limestone, dolomite.
374			MIDDLE		NEVADA FORMATION: Dolomite.
				CONTINUED...	

STRATIGRAPHY[‡]

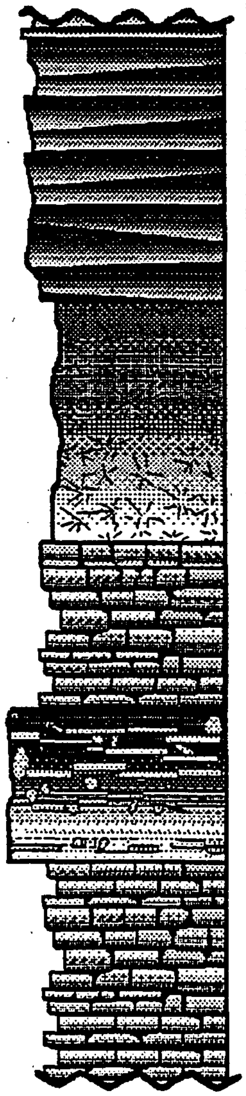
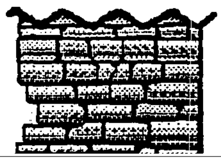


Figure B.1 - (Continued)

AGE[†]	ERA	PERIOD	EPOCH	DOMINANT CHARACTER	FORMATION NAME	STRATIGRAPHY[‡]
438		ORDOVICIAN	LATE	LOWER CARBONATE	ELY SPRINGS DOLOMITE: Limestone, dolomite.	
			MIDDLE		EUREKA QUARTZITE: Quartzite and minor limestone.	
					POGNIP GROUP: ANTELOPE VALLEY LIMESTONE	

Lower Carbonate Rocks

The depositional environment responsible for the lower clastic rocks favored carbonate shelf-type deposition (carbonates and dolomites) later during the middle Cambrian (540 Ma), presumably due to ecstatic (sea level) changes and decreased crotonic erosion. Sediments deposited during this time are called the rocks of the Sauk sequence, named for the Sauk Sea that encroached onto the craton producing an epeiric or shallow inland sea. The regime was interrupted periodically by minor periods of clastic siltstone, clay, and mudstone deposition to the east. Twelve formations have been classified within this sequence. They range from the lowermost Carrara siltstone-limestone formation, forming a transition zone to the underlying clastic rocks, to the Devils Gate limestone. These twelve thick carbonate units collectively account for more than 4,570 m of the total miogeosynclinal stratigraphic column. It is believed they may have been more than 8,230 m thick in the western half of the trough prior to uplift and erosion (Winograd and Thordarson, 1975) during the Mesozoic Era (240 Ma). Ultimately these deposits were subject to the same regional tectonic deformation as

Flat, the unit is upwards of 2,440 m thick. The upper clastic unit, although containing more

In the vicinity of the NTS, the only significant occurrence of intrusive bodies is in the extreme northern and northwestern portions of Yucca Flat. Here, coarse porphyritic monzanite-granite and quartz-monzanite magmas extrude into limestone of the Pognip group and Miocene ash-flow tuff, respectively (Frizzell and Shulters, 1991).

Ash-Flow and Ash-Fall Tuffs

Significant deposition of ash-fall and ash-flow tuff began approximately 30 Ma ago during the Oligocene Epoch. This final phase included silicic volcanism and associated deep crustal extension, producing both horst and graben features and strike slip faulting, operating more or less contemporaneously. Volcanic activity climaxed approximately 11 Ma ago with the eruption of pyroclastic sheets in localized areas of the NTS (Christiansen et al. 1977; Byers

Ash-flow tuffs, however, are consolidated rock formed by catastrophic explosions of hot pyroclastic material (volcanic ash and gases). The resulting deposits exhibit neither bedding nor sorting and could have taken years to cool after emplacement. During cooling, they experience much compaction and internal welding of particles. The degree of welding is generally greater in the center of the unit, resulting in a dense zone of little or no porosity sandwiched between zones of partial welding. Subsequent cooling of these units produces marked jointing and foliation patterns (Ross and Smith, 1961; Smith, 1960). Such distinctions are important because the structure and mode of emplacement between ash-flow and ash-fall tuffs plays a considerable role in determining the difference between the two in water bearing and transmission capabilities.

Basalts and Rhyolites

Silicic volcanic activity in the NTS culminated roughly 10 Ma ago with the formation of the previously mentioned caldera complexes of tuff. The most recent volcanic activity in the NTS according to Wells et al. (1990) has occurred as localized sheet flows of basalt. The youngest basalt exposed at the land surface nearest the RWMS is that of Nye Canyon (Crow, 1990), dated at about 7.31 Ma (RSN, 1994). All the lavas were most prevalent near their respective eruptive centers such as the Timber Mountain Caldera to the northwest of the Area 5 RWMS and the Wahmonie-Salyer Center to the immediate west, near Skull Mountain. The three formations composing the basalt and rhyolite stratigraphic unit are the Basalt of Skull Mountain, Rhyolite of Shoshone Mountain, and the Basalt of Kiwi Mesa. The lava flows are localized in extent; however, they can be of significant thickness close to their origin. Their primary hydrologic importance is restricted to the vicinity of east-central Jackass Flats.

Alluvial Valley Fill Sediments

The most recent deposits in the region are those that fill the valleys and basins due to Pliocene faulting and erosion of the surrounding mountain ranges. They consist of alluvial fan, fluvial, conglomerate, lake bed, and mudflow deposits, and are generally poorly sorted and stratified. The deposits are primarily composed of sub-angular pebbles and cobbles of tuff, carbonate, and quartzite in a sand and silt matrix (RSN, 1991). Alluvial fan deposits are most common at the base of the ridges. Subsequent intermittent streams may carry smaller sized sediment to the lower slopes. The bifurcating braided nature of deposition tends to deposit progressively finer-grained materials further down slope, toward the central playa, as water velocity lessens. Some accumulation of calcium carbonate has been observed in the B and BC horizons as coatings on clasts and pebbles. The alluvium, very deep in most valleys within the NTS, is estimated to be at least 500 to 600 m beneath central Yucca Flat and Frenchman Flat, and about 320 m beneath central Jackass Flats.

SEISMOLOGICAL RISK ANALYSIS

Intensities of Historical Earthquakes

Although the western margin of the NTS lies within an area believed to have a high risk for potential seismicity, activity has historically been low to moderate. The most recent earthquake of significance was of magnitude 5.6, occurring on June 29, 1992. Its epicenter was approximately 15 km to the southwest of the Area 5 RWMS near Skull Mountain, at a depth of 10 km. The Area 5 RWMS was unaffected. There is a marked trend for increased seismic events in southern Nevada having a magnitude greater than 5.0 on the Richter scale to the northwest of the NTS. This parallels pre-existing planes of weakness thought due to a 250 km long rift that formed 14 to 17 Ma ago in north central Nevada (Stewart et al. 1975;

possibility for the occurrence of a large earthquake somewhere within the NTS during the next 10,000 to 15,000 years.

Table B.1. Compilation of estimated seismic hazard analyses for the NTS.

Seismic Hazard Analysis			
Potential Maximum Earthquake Magnitude[†]	**Peak Ground Acceleration**	**Return Period**	**Source**
7	0.7 g	15.0 Ka	Rogers et al. (1977)
6.8	0.7 g	12.7 Ka	Campbell (1980)
5.8-6.1	0.9 g	-	Hannon and McKague (1975)

[†]Richter Scale

An approximation of the seismic risk to the NTS region can be calculated using the binomial distribution (Parzen, 1960). It is common to examine a sequence of independent events for which the outcome is either a success (an earthquake of magnitude 6.8 or greater occurs in a given year) or failure (no earthquake of magnitude 6.8 or greater occurs). This assumes that the probability (p) of a success remains constant over time and that each year represents an independent Bernoulli trial. Given these assumptions, the risk (probability that at least one earthquake will occur over a given period) can be calculated from the well-known binomial distribution.

If there are n independent trials and, on each trial the probability of a success is p, then for $x = 0, 1, 2, \ldots, n$,

$$P(\textit{number of successes is } x) = \binom{n}{x} p^{x}(1-p)^{n-x} \tag{1}$$

where:

$$\binom{n}{x} = \frac{n!}{x!\,(n-x)!} \; \textit{for } x = 0, 1, 2, \ldots, n. \tag{2}$$

Since the probability of a success (earthquake of magnitude 6.8 or greater) is assumed to be a constant $7.87 \times 10^{-5}\,yr^{-1}$ (1/12,700 yr), and since the probability that there are 0, 1, 2,..., 10,000 earthquakes sums to one, the probability there are one or more earthquakes of magnitude 6.8 or greater is:

$$\begin{aligned} &Risk = \\ &1 - P(no\ successes) = \\ &1 - \binom{10000}{0} (7.87 \times 10^{-5})^{0} (1 - 7.87 \times 10^{-5})^{10000} = 0.545. \end{aligned} \tag{3}$$

These calculations suggest there is about a 50 percent chance of one or more earthquakes greater than 6.8 in the next 10,000 years. Note that if the calculations are repeated with the less conservative return time of 15,000 years, the probability of an earthquake falls to 0.486.

Despite the moderate risk of seismic damage, the limited use of engineered structures at Area 5 RWMS makes the site intrinsically less prone to significant earthquake damage than an above-ground facility or a facility using engineered below-ground vaults. Unless a major earthquake centered on the Area 5 RWMS occurred, at worst only limited compaction, caused by the consolidation of alluvium, might be expected. Given the large return times associated with the largest events coupled with the small likelihood that an event would be centered upon the Area 5 RWMS, it is unlikely that the integrity of the RWMS would be compromised.

VOLCANIC RISK ANALYSIS

Data concerning the hazards of future volcanism in the NTS region have been acquired from ongoing assessments of the volcanic hazard at Yucca Mountain, located approximately 45 km west of the RWMS. The close proximity of Yucca Mountain to the RWMS suggests that the volcanic hazard associated at the RWMS can be garnered from the data gathered at Yucca Mountain.

Crowe et al. (1983) concluded that further silicic volcanism was not realistic, given the age evidence by Christiansen et al. (1977) and Byers et al. (1976) for the ash-flow and ash-fall tuffs in nearby caldera systems. The most recent volcanism, associated with the Death Valley-Pancake Range Volcanic Belt (Wells et al. 1990), has been basaltic. The Death Valley-Pancake Range Volcanic Belt, a 50 km wide swath of activity that transects the NTS trending north-south throughout southern Nevada, is characterized by cinder cones and lava flows of limited extent (Figure B.2). Crowe and Carr (1980) identified four tectonic settings within the NTS where the risk of recurrent basaltic volcanism was assessed. Their data suggest the immediate vicinity of nearby caldera ring fracture zones or rift grabens possess the greatest likelihood for renewed volcanism. Ongoing studies at the proposed high-level [illegible]

Mountain-Oasis Valley Caldera and Lathrop Wells Volcanic Fields (Byers et al. 1976; Crowe, 1990). Closer to the Area 5 RWMS, approximately 19 km west-southwest, lays the Wahmonie-Salyer Volcanic Center. The youngest basalt exposed at the land surface nearest the RWMS is that of Nye Canyon (Crow, 1990), dated at about 7.31 Ma (RSN, 1994).

In Frenchman Flat near the Area 5 RWMS, there is no evidence of basalt activity on the surface. However, basalt flow and rubble, intercalated with near subsurface alluvium, occur in two nearby boreholes and Pilot Well Ue3PW-3. Basalt flows were encountered 270 m below the surface, approximately 2.4 km north of the Area 5 RWMS in borehole UE5i and roughly 2.7 km to the north-northeast in borehole U5k. In U5k, an interval of basalt rubble occurs 275 m below the surface (Carr et al. 1975). The ages of the flows in UE5i and U5k

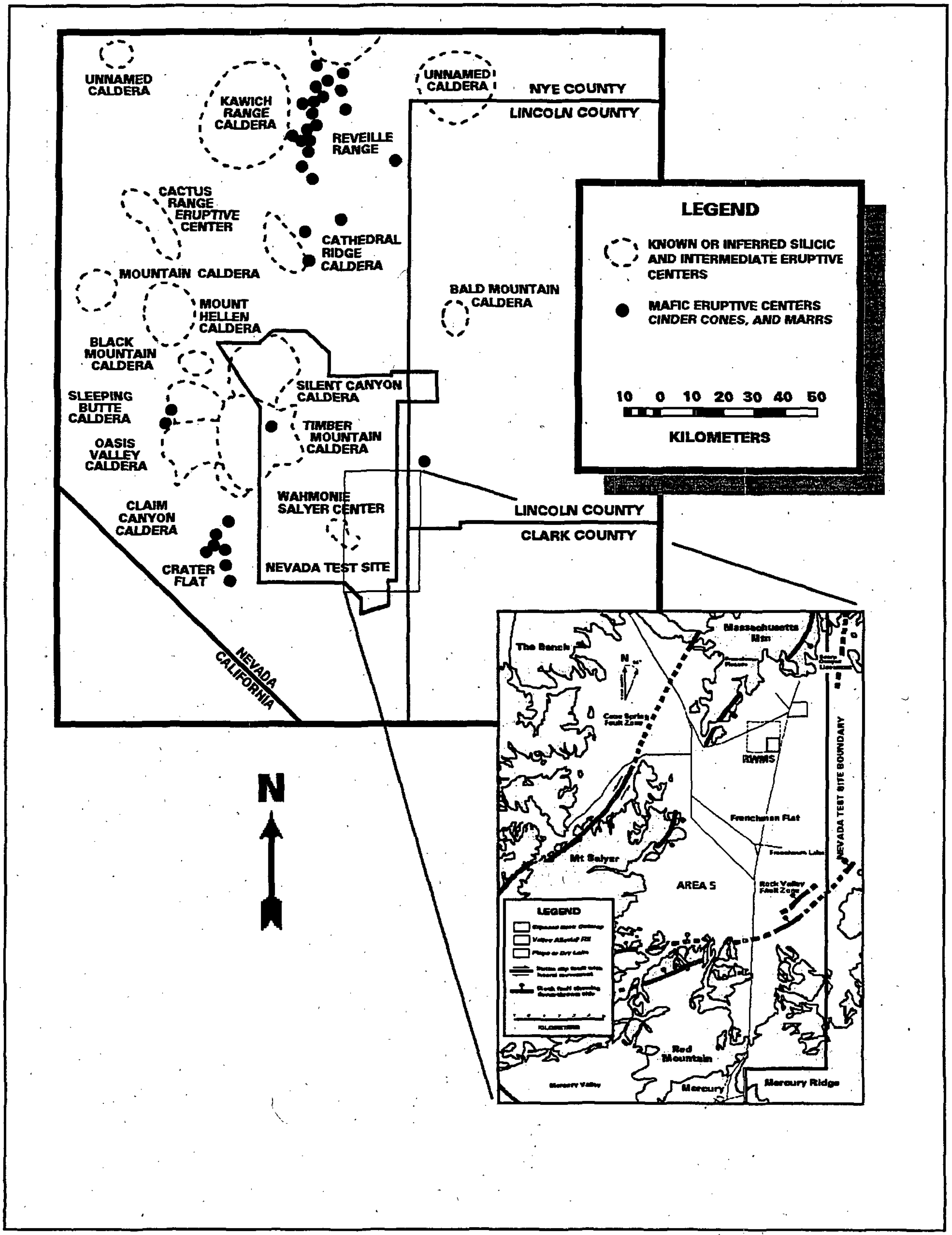


Figure B.2 - Tertiary volcanic centers in the NTS region (adapted from Case et al. 1984).

Projected Volcanic Hazard

It is believed that the influence of renewed basaltic volcanism would be much more localized than that of earlier silicic eruptions. The extent of deposition would be restricted to the immediate vicinity of the eruption centers, probably within 2 to 10 km of the cinder cone and associated lava sheet (Case et al. 1984). K-Ar dating methods, coupled with geomorphic and pedogenic comparisons with other nearby volcanic regions, indicate that volcanism is unlikely to have any impact on the integrity of the Area 5 RWMS in the near future, because of the large time scales involved.

An unusually conservative estimate for volcanism in the NTS area has been given by Wells et al. (1990), who suggested that the most recent activity (the Lathrop Wells Cone) near Yucca Mountain may have taken place only 20 Ka ago, based on a comparison to a similar field (Cima) in southern California. This estimate however, neglects the K-Ar data that dates the previously mentioned basalt flows at around 8.5 Ma (RSN, 1994). Even in view of this conservative estimate, it is reasonable to speculate that the estimated hazard from renewed volcanic activity is small when compared to a 1,000 or 10,000-year post-closure period for waste isolation. Further evidence supporting a low hazard was provided by Crowe and Carr (1980). They showed an annual hazard probability for a high-level waste repository

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APPENDIX C

RESPONSE TO THE USDOE PEER REVIEW PANEL RECOMMENDATIONS FOR REVISION 1 OF THE AREA 5 RADIOACTIVE WASTE MANAGEMENT SITE PERFORMANCE ASSESSMENT

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Responses to General Recommendations

1. Recommendation: Incorporate new and soon-to-be-available hydrogeological data in the analysis.

   Response: Since completion of revision 1, REECo (1993a, 1993b, 1993c) has reported the results of hydrogeological characterization studies based on 10 shallow boreholes, existing trenches, and 3 deep boreholes reaching the uppermost aquifer. These reports describe hydrogeological parameters for alluvium and the results of chemical and isotopic tracer studies.

   These investigations have shown the alluvium is homogeneous with respect to lithology, mineralogy, particle size distribution, porosity, saturated hydraulic

The scope of inventory records included has been modified. The inventory of previously disposed wastes has been limited to disposals occurring since the implementation of USDOE Order 5820.2A. All wastes and waste disposal units active during this interval, including classified and unclassified wastes, GCD waste and mixed waste, were considered.

The inventory recorded in the site database has been critically assessed and revised. Inventory records were found to include several incorrect or duplicate entries. These errors were corrected. Waste codes appearing in the inventory, MFP and PU-52, were assigned isotopic compositions. The additional isotopes added to the inventory from waste codes was negligible for MFP, but significant for Pu isotopes. The under-reporting of low specific activity fission products, such as ^{99}Tc and ^{129}I, was assessed by identifying all waste streams containing mixed fission products. Only two such waste streams, whose total activity was negligible, were identified. Nevertheless, activities of long-lived fission products in these waste streams were estimated and added to the inventory. The final and most significant revision involved unreported U isotopes. The waste streams of each generator producing U bearing waste streams was evaluated. Based on this review, additional uranium activity was added to the inventory. These additions significantly increasing the ^{234}U and ^{235}U inventories.

The future inventory was projected from wastes received during FY89 to FY93, a period when most generators were engaged predominately in decommissioning and environmental restoration. This inventory was prepared and analyzed to show that there is reasonable assurance that past waste disposal meets the performance objectives and that the NTS can continue to receive the same waste streams and reasonably expect to be in compliance. Final assurance of meeting the performance objectives will be provided by developing new waste acceptance criteria based on these analyses and applying these criteria to future waste shipments. Future revision(s) of the performance assessment will address possible changes to the inventory.

3. Recommendation: Expand the analysis of daughter radionuclides of long-lived radioisotopes.

Response: All analyses have been modified to include progeny. Progeny with half-lives long enough that secular or transient equilibrium is not possible in 100 years have been calculated explicitly. Nuclides with shorter half-lives have been assumed to be in secular or transient equilibrium with the parent.

4. Recommendation: Analyze upward versus downward migration.

Response: Scenarios used in this performance assessment were developed by screening a comprehensive list of features, events, and processes that might affect performance. The only process considered capable of inducing "downward migration" was liquid advection to the groundwater (recharge). Recent site characterization data, presented in Section 2.4.2 and analyses described in Section 3.1.1.1, demonstrate that recharge is negligible. Processes considered capable of inducing "upward" migration were: liquid advection, solute diffusion in the liquid phase, gaseous diffusion, gaseous advection, plant uptake, and bioturbation. Modeling, discussed in Section 3.1.1.1, has shown that near-surface alluvium at the NTS is too dry for significant liquid advection or diffusion. Both processes were eliminated from scenario development. Advection and diffusion of gases, plant uptake and bioturbation, and the remaining processes for upward migration were retained for scenario development.

Responses to Detailed Comments

1. Comment: The document should have more figures and the clarity of the figures needs to be improved.

   Response: Many figures have been added to the document including many developed specifically for the performance assessment.

2. Comment: The Area 5 performance assessment should have one lead person who serves as the focal point for preparing the document.

   Response: The Area 5 performance assessment has always been managed by a single person. At the time of review of revision 1, the preparer had left the company and a replacement had not been selected. The current revision was prepared by a team at REECo, with extensive support from Oak Ridge National Laboratory. Greg Shott of REECo has managed preparation of this revision.

3. Comment: The performance assessment is generally over conservative and a greater degree of reality (site-specificity) should be incorporated in the rewrite.

Response: Two additional sources of site-specific information have been used to prepare this revision. First, extensive hydrogeological site characterization data has become available since the last revision. This has lead to a more realistic conceptual model of site hydrology. Second, a detailed review of site-specific NTS literature was undertaken. Many relevant ecological and radioecological investigations have been conducted at the NTS. The results of this review and of site characterization studies have been incorporated in Chapter 2. Finally, the overall philosophy used to develop scenarios and parameterize mathematical models has changed. The release and pathway scenarios analyzed represent the most likely future state of the disposal site, given what is currently known. The parameter values used are the best-estimate value for cases when sufficient site-specific data was available. In cases where reliable data were lacking, conservative parameter values were substituted.

4. Comment: The reason for the document being revision 1 should be explained.

Response: The first draft of the Area 5 Performance Assessment was an unnumbered version prepared by the Idaho National Engineering Laboratory. Revision 1 was a technical rewrite prepared by the REECo project manager, based on internal review. This current version, revision 2, uses much of the original methodology of revision 1, but with new site-specific data and revised conceptual models as suggested by the USDOE Peer Review Panel.

5. Comment: Mixed waste associated with the Area 5 disposal needs to be better discussed and explained. Also, the potential impact of not considering the contribution of buried commingled TRU and LLW should be discussed.

Response: Mixed waste disposal at the Area 5 RWMS has occurred only in Pit 3 and has been very limited in volume. Mixed waste disposal has been discussed in Section 2.9.1.1. TRU waste disposals all pre-date the implementation of USDOE Order 5820.2A and are therefore not considered here. TRU waste disposal is the subject of a separate performance assessment being prepared by Sandia National Laboratories to meet the requirements of 40 CFR 191.

6. Comment: Radium and gross alpha may be appropriate to add in Table 1.1 under 5400.5 and EPA.

   Response: Groundwater protection requirements have been revised in Section 1.3, but are irrelevant because groundwater has been eliminated as a credible pathway.

7. Comment: The new Radiation Control Manual provisions should be considered in the performance objective discussion.

   Response: The Radiation Control Manual was considered in the development of performance objectives, but was not ultimately included. The Radiation Control Manual is an operational radiation protection plan. It is not relevant after USDOE operations cease.

8. Comment: The discussion of 40 CFR 193 should be deleted.

   Response: 40 CFR 193 has not been considered in revision 2.

9. Comment: It is stated that USDOE came under RCRA in 1986. USDOE actually came under RCRA in 1984.

   Response: The comment is noted. The statement has been deleted.

10. Comment: The potential impacts of flash floods and freeze thaw cycles on the integrity of long-term waste confinement should be discussed.

    Response: The consequence of flash flooding has been assumed to be erosion or channeling to the depth of buried waste. This event was considered in scenario development. However, site characterization data (Section 2.4.1.1) indicates that it is improbable that a channel deep enough to reach buried waste could form at the Area 5 RWMS in the next 10,000 years. Therefore, no flooding scenario was modeled.

    Freeze thaw cycles might result in some change in cover function or integrity. Freeze thaw cycles were not discussed in the performance assessment because they are generally unimportant in this region. Freezing temperatures occur infrequently and usually are limited to a few hours in the evening. Consequently, surface soils rarely freeze below a depth of a few centimeters. When freezing occurs, the dryness of the soils, combined with the shallow depth of freezing, causes very little expansion. Freeze thaw cycles are not expected to have any significant impacts.

11. Comment: Figure 2-3, which is on page 14, is not discussed until page 33. The discussion is difficult to reconcile with the figure.

Response: All the figures and text describing the RWMS have been revised and appear in Section 2.9.

12. Comment: There should be a map that shows Area 5 and ancillary facilities such as the potable water wells, the three other radioactive waste management sites, and the liquid leach field on a larger scale. Discuss the operational status of the leach field and three other burial sites, their proximity to the Area 5 RWMS, and how they impact the Area 5 RWMS performance.

Response: All new figures and text describing the facility have been prepared and appear in Sections 2.1 and 2.9. The leach field at the Area 5 RWMS has never been used and there are no plans to activate it. There is one other waste disposal site, the Area 3 RWMS, located 27 km to the north. Each site is the subject of separate assessments.

13. Comment: A geologic/lithologic cross section of the Area 5 from surface to bedrock should be included.

Response: The geology and lithology of the NTS has been described in Section 2.4 and Appendix B. A lithology cross section appears in Appendix B.

14. Comment: Is the "restrictive hardpan" the same as the "caliche beds" referred to later in the intruder analysis? The areal distribution and location of the restrictive hardpans should be discussed, as well as the depth of occurrence.

Response: Revision 1 of the performance assessment hypothesized the existence of caliche at the Area 5 RWMS based of its common occurrence within calcareous soils in southern Nevada. Calcium carbonate has been observed to form coatings, filaments, and small masses within some soil horizons at the RWMS (Snyder et al. 1994), but caliche layers have never been observed in trenches or boreholes (REECo, 1993a, 1993b, 1993c; Snyder and Gustafson, 1994; Snyder, in press). Alluvium at the RWMS is derived predominately from pyroclastic volcanic rocks (Snyder et al. 1994) and is less likely to develop extensive accumulations of carbonates. Based on these data, the current conceptual model of site geology USDOEs not include the existence of any caliche beds or restrictive hardpans sufficiently developed to affect hydrology.

15. Comment: The potential impact of seismic activity on long-term confinement should be discussed.

    Response: The seismic hazard at the Area 5 RWMS has been assessed and described in Appendix B. Seismic activity was an event/process considered in scenario development. The maximum predicted earthquakes for the NTS range from 5.8 to 7.0 on the Richter scale. The largest magnitude quakes have been estimated to re-occur at a frequency of 12,700 to 15,000 years. Under the model of Appendix B, with the additional assumption that no more than one earthquake will occur per year, the probability of one or fewer earthquakes in the next 10,000 years is:

$$\binom{10000}{0} p^{0}(1-p)^{10000} + \binom{10000}{1} p^{1}(1-p)^{9999}$$

    where p = 1/12,700, or P(Number of earthquakes ≤ 1) = 0.813. The probability of one or more earthquakes is 0.545. Since the RWMS USDOEs not rely on engineered barriers, it is unlikely that a single earthquake will significantly impact performance. This event was not ultimately included in scenario development because it is not expect to have significant consequences in the next 10,000 years.

16. Comment: The yields, as well as the water quality, of each aquifer should be discussed.

    Response: The properties of aquifers beneath the RWMS are discussed in Section 2.4.1.2. The water quality of the uppermost aquifer is presented in Section 2.4.2.3.

17. Comment: Another cross section showing the water table and various subsurface features, such as the aquifers/aquitard, should be included. The homogenous nature of the NTS Area 5 soil and lack of fracture zones needs to be further discussed.

Response: Cross sections showing hydrologic units appear in Sections 2.4.1.2.1 and 2.4.1.2.2. The homogenous nature of the alluvium is described in Sections 2.3.2.4 and 2.4.2.2.

18. Comment: Why USDOEs the performance assessment evaluate the performance of waste disposed prior to 1988? Is the inclusion of the "old" waste intended to provide a basis to project the inventory? If so, what is the effect of including cardboard boxes?

    Response: The performance assessment has been revised to consider only waste disposed of since the implementation of USDOE Order 5820.2A.

19. Comment: The inventory has apparently strange ratios of activities. In particular, the ratio of ^{137}Cs to ^{90}Sr USDOEs not coincide with the normal fission product distribution. The amounts of some uranium isotopes seems inconsistent. The listing of ^{129}I as zero activity is suspicious. Tin-126 has been omitted from the inventory.

    Response: Numerous waste generators ship numerous waste streams to the Area 5 RWMS. The isotopic ratios of the total inventory should not be expected to conform to that of any single process. The activity ratios of pre-1988 fission products will be altered by the presence of very large sealed sources including radioisotope thermal generators. Review of post-1988 fission product waste streams reveals that these waste streams mostly originate from isotopically pure sources. Mixed fission product waste streams have been identified and estimated activities of ^{129}I and ^{126}Sn added to the inventory. These corrections proved to be minor. Similarly, uranium isotope ratios have been evaluated on a generator basis and fiscal year basis and corrected using the best available information. Uranium corrections proved to be significant. The revised inventory is discussed in Section 2.10.

20. Comment: PU-51 and PU-52 should not be mentioned or should be carefully explained.

    Response: Post-1988 inventory records include only Pu-52. This code has been converted to isotopic activities in Section 2.10.

21. Comment: The presentation of the inventory makes use of too many significant figures; so many significant figures imputes too much accuracy to the inventory. Also, there is no discussion of the uncertainty in the inventory.

Response: It is impossible to determine the number of significant figures in inventory records. To do so, one would have to examine each disposal record and assume the generator reported the correct number of significant figures. This revision presents the inventory to two significant figures.

The inventory presented in the performance assessment is highly uncertain. There are little or no data available that could be used to estimate uncertainties. Useful data would include generator estimates of uncertainty, descriptions of waste characterization methods and description of generation processes. Unfortunately, these data are not consistently reported by the generators and are not available in database records. Due to the large number of generators and waste streams, evaluating the available information would be extremely labor intensive and of dubious value due to inconsistent reporting. Therefore, no quantitative estimates of inventory uncertainty are available. Generators usually report that their activity concentration estimates are conservative. This may be accurate for major nuclides expected for the waste streams. However, there may be additional nuclides that tend not to be reported due to measurement difficulties. For example, a generator with a depleted uranium waste stream might over report ^{238}U for conservatism, but not report any activity for ^{234}U. It is difficult to draw even general conclusions regarding the

24. Comment: The performance assessment should take into account the changing mission of the NTS, and clearly discuss the method of projecting the waste inventory and associated uncertainties. The NTS should consider whether, in the face of uncertain future receipts of waste, the performance assessment should be used to develop inventory limits.

Response: The method of projecting future waste inventory and its uncertainties has been discussed in Section 3.2.1. Results from this performance assessment will be used to develop waste acceptance criteria.

25. Comment: The index calculated in Equations 3-1 and 3-2 is not dimensionless. This may result in the relative calculations being skewed. This could be corrected, at least in part, by using R_d instead of K_d. Also, the inclusion of daughters is not well explained. It would be helpful to show detailed calculations. It is also not clear why tritium, with such a high inventory, was screened out. Explain why the indices for the intruder scenarios are not included. The breathing rate term used in Equation 3-2 is not consistent with the rate used later in the document. The screening methodology presented USDOEs not seem to use screening appropriate to the pathway being considered.

Response: The hazard index used in the previous versions USDOEs not appear in Revision 2. Tritium has not been screened out of this analysis. Screening has not been performed for the intruder scenarios since results are needed to develop waste acceptance criteria for all nuclides likely to be in NTS waste streams.

26. Comment: It would help the reviewer if more example calculations and tables of input data and intermediate results were presented.

Response: This version of the performance assessment presents more intermediate results which should aid all reviewers.

27. Comment: Table 3-2, on page 45, includes ^{235}U, but ^{235}U was not included in Table 3-1. This should be explained.

Response: This was likely an error. These sections have been revised.

28. Comment: On page 46, in Section 3.2.2, the basis for the assumption that one-half of the intruder's food comes from the agriculture scenario is not presented.

Response: Developing a small number of site-specific deterministic intruder scenarios that represent all realistic or probable future events is not feasible. Therefore, established intruder scenarios have been used. Parameters have been adjusted, as thought reasonable for southern Nevada. Scenario features have been deleted if physically impossible. Since several previously used scenarios include agricultural pathways, agriculture was considered in the intruder scenarios. Agricultural features were retained because these features are not physically impossible at the NTS. Grazing is a wide-spread commercial agricultural activity in Nevada. Irrigated hay crops are produced in some areas were water is available. Although cultivation of food crops is commercially insignificant, home grown vegetables are reported to be widely available to rural residents near the NTS. Agricultural pathways can be eliminated at the NTS only if one is willing to make assumptions about future human period, they were included to maintain the mass balance of the near field model (i.e., the inventory is not entirely transported to the unsaturated zone)." These two sentences seem to be contradictory.

Response: This portion of the analysis has been revised. Any contradictions have been eliminated.

31. Comment: On page 52, in Section 3.3.2, the "restrictive hardpan" or caliche beds are not considered in the conceptual model. Their absence is not explained. The discussion of the use of Monte Carlo technique is too brief. Also, the possibility of upward migration in the vadose zone was apparently not considered.

Response: The new conceptual model of site performance USDOEs not include the existence of caliche beds developed to the extent that they would affect the hydrologic conceptual model. See detailed comment 14 for more details. The Monte Carlo technique was not used in this revision. See general recommendation 4 for details regarding upward migration.

32. Comment: The truncation of the conceptual model 100 m south of the receptor location may not be appropriate, depending on the nature of the aquifer. A simple figure depicting the conceptual model would greatly aid understanding what is being analyzed. No mention is made relative to the predicted uncertainty in the inventory affecting the predicted concentration results.

Response: These comments pertain to the groundwater pathway. The revised conceptual model USDOEs not include a groundwater pathway.

33. Comment: Although the NTS has evidence that the RWMS is accumulating sediment, the performance assessment analyzed a scenario in which the cover soil erodes. This may be an appropriate conservatism, but the degree of conservatism is not addressed in the performance evaluation section. The consideration of channeling after erosion may be too conservative. The assumed intruder occupation of the site 100 years after the end of institutional control USDOEs not consider the buildup of radon or other daughter products.

Response: The conceptual model of the waste cell has been revised. The new conceptual model makes the assumption that 2.4 m of cover is present throughout the 10,000-year compliance interval. This is a conservative assumption, based on estimated erosion and sediment accumulation rates and preliminary conceptual designs for the final closure cap.

Channeling to the depth of buried waste was an event considered in scenario development. It is very unlikely that a channel will ever reach the depth of buried waste. Currently, channels deeper than 1 m are not observed in the area (RSN, 1991). A recent analyses suggest that the maximum channel depth expected for 10,000 years is 1.5 m (Snyder et al. in press). It was concluded that channeling 2.4 m to buried waste was not credible.

Intruder analyses have been extended to the time of maximum dose considering the ingrowth of all progeny.

34. Comment: The statement on page 55 that basements are not built in the Las Vegas area because of caliche is not correct and needs to be modified.

Response: Most residential structures built in southern Nevada are slab on grade structures. Slab on grade structures are built most often because of their lower cost per unit area. Basement construction was originally selected by the USNRC (USNRC, 1981) as one of many possible excavation scenarios that could occur if an intruder occupied the burial grounds. Basement construction by the intruder has been maintained because it is physically possible at the Area 5 RWMS. There are no subsurface geologic structures that could eliminate basement construction. Even if basement construction could be eliminated based on current practice, excavation for any number of other reasons including septic tanks, utility trenches, or underground storage tanks is still possible. Basement construction can be eliminated at the NTS only by making assumptions about future human behavior. Relying on assumptions about future human behavior to protect the public was considered to be an indefensible position. Therefore, construction of a basement in the intruder-construction and intruder-agriculture scenarios were retained.

35. Comment: The analysis of atmospheric dose is confusing. The factor χ/Q has units of seconds per cubic meter. How can this be multiplied by a dose and the product results in a dose? Also, there is no justification for the statement that wind speed of 1 m/s and stability class F is bounding.

Response: The atmospheric dispersion modeling has been revised using CAP88-PC. The meteorological data used represents 4 years of data collected at Frenchman Flat.

36. Comment: The discussion of groundwater dose USDOEs not consider that daughters of ^{238}U will not be in secular equilibrium at the early time periods. It would be helpful to show the dose contributions from parents and daughter radionuclides.

Response: The current version of the performance assessment USDOEs not include a groundwater pathway analysis.

37. Comment: Uranium represents both a radiological and non-radiological health hazard. If considerable amounts of uranium are expected to be disposed at this site, it might be worthwhile to conduct a screening level analysis to determine whether the nonradiological hazard is important. In this regard, the solubility of the uranium compounds must be characterized.

Response: The non-radiological health hazard of uranium is limiting only for the higher radiological exposures permitted for occupational workers. Dose limits contained in environmental regulations are generally too low to cause any potential nephrotoxicity. This can be confirmed by determining the steady state kidney burden resulting from a constant intake that will deliver the applicable dose limit. In all cases, the isotope ^{238}U and inhalation Class D uranium produce the most conservative results (Kocker, 1989) and will be used throughout. The stochastic annual limit on intake (SALI) for Class D ^{238}U is 2 μCi for inhalation and 20 μCi for ingestion (ICRP, 1979). The SALI produces a CEDE of 5 rem in Reference Man. For an intruder dose limit of 100 mrem, the limits for inhalation and ingestion become 1/50 of the limit or 0.04 μCi for inhalation and 0.4 μCi for ingestion. The steady state organ burden resulting from the 100 mrem intake rate can be estimated from ICRP models (ICRP, 1979) (Table D.1). The ICRP has reported that, of uranium reaching the transfer compartment, 0.12 goes to a kidney compartment with a half-life of 6 days and 0.00052 goes to a kidney compartment with a half-life of 1500 days.

Table C.1. ICRP data used to assess non-radiological risk of Class D ^{238}U to the kidney.

Parameter	Class D Uranium-238	
	Inhalation	Ingestion
[illegible]	[illegible]	[illegible]

intruders exposed at the 100 mrem yr^{-1} limit will have radiological doses from nuclides that do not affect the kidney. Individuals exposed at the 25 mrem yr^{-1} all pathways limit will be well protected. The only situation where the nephrotoxicity limit appears limiting is for an intruder receiving 100 mrem yr^{-1} from pure class D ^{238}U. This is not a credible exposure scenario and nephrotoxicity was not considered further.

38. Comment: The analysis of intrusion doses claims to account for doses due to all daughter nuclides. However, the intrusion calculations were done for only one time, namely 100 years after site closure.

Response: The intruder doses have been determined at 100 years and at the time of maximum dose considering the ingrowth of all progeny.

39. Comment: On page 64, the statement is made that no credit is taken for the metallic form of uranium. However, the solubility limit for uranium isotopes is assumed to be 1E-4 mol/l. This implies that credit for the low solubility of uranium metal in water was considered. If NTS is planning to receive uranium from other sources, such as Fernald, the chemical form of the uranium would have to be considered.

Response: The revised performance assessment includes no water-mediated transport. Therefore, no solubility limit data are needed. The NTS has received uranium primarily from the Aberdeen Proving Grounds, FERMCO, and General Atomics. These shipments include many waste streams and chemical forms of uranium. No attempt was made to determine the chemical forms of uranium present, as this information is not available in NTS databases and may be unreported by the generators in their applications. Instead, conservative values were selected for model parameters sensitive to chemical form.

40. Comment: There are some problems with the tables for the intruder analyses.

Response: The intruder analyses have been performed again. Completely revised text and tables have been provided.

41. Comment: In the analysis of sensitivity and uncertainty in Section 4.3, there was no consideration of the effect of the uncertainty in the inventory. Also, the response of the computed doses to changes in K_d values was not assessed.

Response: The sensitivity and uncertainty analyses have been revised to consider inventory. The current performance assessment, with no water-mediated transport pathways, USDOEs not use K_d values.

42. Comment: The performance evaluation chapter is weak and should be expanded. State and local requirements for groundwater protection should be discussed.

Response: The performance evaluation chapter has been rewritten. State and local groundwater protection standards have been discussed in Section 1.3.1.

43. Comment: On pages 85 and 86, the discussion of "validating" a one-dimensional (1D) code versus a two-dimensional (2D) code and "validating" a 2D code versus a three- dimensional (3D) code implies that a 3D code is less subject to uncertainty than 1D or 2D code. Also, there is no discussion of validating any code versus real data. Are there no plans to provide confidence in whatever code is used by comparing code results to actual data?

Response: The revised performance assessment used different computer codes than the previous version. All codes are one-dimensional. No attempt has been made to validate (compare predictions and data) any computer models. The only relevant data likely to become available are for hydrology models. Lysimeter and micrometerology experiments, underway at the Area 5 RWMS, will eventually provide data that could be used to validate hydrology codes. Rather than attempt validation, this performance assessment has focused on verification (comparing model output with known analytical solutions to selected problems and performing benchmark tests with well accepted codes). All models used have been thoroughly verified.

44. Comment: The intruder scenario assumptions given on page 92 are largely unjustified.

Response: The intruder scenario adopted for this performance assessment are based on scenarios used for virtually every assessment performed in the United States. These scenarios have previously been described by USNRC (1981) and Kennedy and Peloquin (1988). Scenario elements have been eliminated when deemed physically impossible for the NTS (e.g. irrigation with contaminated groundwater). Parameters have been altered from those of standard scenarios when there was good evidence that different values were appropriate at NTS.

45. Comment: The exposure pathways listed on page 94 do not include dermal absorption and inhalation of tritium while showering.

Response: The only source of water at the Area 5 RWMS is deep groundwater or water imported from a distant site. Under the revised conceptual models, neither source is expected to be contaminated. Therefore, the missing pathways are not appropriate.

46. Comment: It is not clear whether rainsplash was considered as a mechanism for transferring contaminated soil particles to leaf surfaces. Also, the general question of ingestion of soil was not addressed.

Response: The pathway scenarios include soil ingestion by the public and livestock. The intruder analysis includes soil ingestion by livestock and residents also. Neither analysis includes rainsplash. However, dry deposition of suspended soil on plant surfaces is included. In the intruder analysis, inhalation and external irradiation dominate the exposure pathways. Ingestion pathways are a small fraction of the total dose and rainsplash will contribute little additional dose considering the infrequent rainfall.

47. Comment: On page 106, transport is indicated to take place between the surface soil and compartment 14. However, in Figure B-2, no connection is shown between compartments 1 and 14.

Response: The near field transport model has been revised and the inconsistency removed.

48. Comment: On page 111, the solubility limit for plutonium and uranium isotopes is assumed to be 1E-04 mol/l. What is the basis for the assumption? What chemical form is implied by this solubility?

Response: The current conceptual model includes no water-mediated transport mechanisms. Therefore, there are no solubility limits in the revised performance assessment.

49. Comment: In Appendix E, "Tritium Dose Assessment," it is stated that only environmental monitoring data were used to estimate the annual tritium emission and that the estimated emission is 0.68 Ci. However, there is no data presented to support the 0.68 Ci/yr, nor is there any discussion as to the observed variability in the emission rate. Additionally, there is no justification for extrapolating the current rate onto the future.

In this appendix, three calculations are presented. Although these calculations seem to be straightforward, an audit of the calculations gives, in each case, a result that is one order of magnitude less than that presented in the report.

Response: Tritium release in the revised performance assessment has been calculated using a simple diffusion model. The appropriate sections have been revised.

50. Comment: Although surface water flow patterns are discussed, no diagrams are provided. There is no section in the performance assessment listing the preparers, their contribution to the performance assessment, or their expertise and experience. In addition, USDOE/LLW-93 "Performance Assessment Review Guide for USDOE Low-Level Radioactive Waste Disposal Facilities," recommends discussing the QA/QC aspects of the performance assessment. These sections should be included in the revision.

Response: The information requested has been included. Surface water flow with figures is presented in Section 2.4.1.1. The preparers are listed in Chapter 6. Quality assurance is discussed in Section 3.7.

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APPENDIX D

HYDROLOGY CONCEPTUAL MODEL DEVELOPMENT

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1.0 HYDROLOGY CONCEPTUAL MODEL DEVELOPMENT

This appendix describes the development of the hydrology conceptual model for the Area 5 RWMS. The hydrology conceptual model describes the processes controlling the movement of water within the vadose. The model has been interpreted to identify processes that could lead to the release of radionuclides from the source term.

Hydrologic and climatic characterization data is available for the NTS (Winograd and Thordarson, 1975; Schoff and Moore, 1964), and for the Area 5 RWMS (REECo, 1993a, 1993b, 1993c; French, 1993; Snyder et al. 1993; RSN, 1991a, 1991b; Sully et al. 1995; Lindstrom et al. 1992; and Detty et al. 1993). Additional studies have been performed to determine the hydrologic behavior of other sites with similar environments (Gee et al. 1994; Fouty, 1989; Fischer, 1992; Scanlon, 1994; Scanlon and Milly, 1994; and Scanlon et al. 1991). These and other works may be applied, by analogy, to the performance assessment of the Area 5 RWMS.

A preliminary hydrology conceptual model has been developed from site-specific hydrologic data (Section 2.4.2.2.1). This model proposes that the movement of moisture in the vadose zone beneath the Area 5 RWMS can be delineated into three regions of liquid movement (Figure 2.22):

- Zone I: An upper zone, approximately 35 m in depth, where a high evapotranspiration rate at the surface creates a large negative hydraulic potential for upward liquid flow and drying at the near-surface.

- Zone II: An intermediate zone from about 35 m below the surface down to 150 to 220 m, dominated by gravity drainage or vertical downward flow.

- Zone III: A lower zone, immediately above the water table, where the hydraulic potential is near zero and the water is under a capillary fringe condition with relatively static conditions producing little flow.

Additionally, site characterization data indicates that the alluvium can be considered as an isotropic homogeneous medium (Sully et al. 1993; Istok et al. 1994) which implies that a one-dimensional analysis should be sufficient to determine the magnitude of water fluxes. This appendix focuses on the processes controlling the movement of water in Zone I and their implications for radionuclide transport. The upper 35 m of the alluvium (Zone 1) is emphasized because all disposal units are within this zone.

Five hydrologic processes have the potential to affect water movement within Zone I (Figure D.1). These processes are:

- transient precipitation-infiltration events,
- variable seasonal evapotranspiration,
- vapor flow driven by thermal gradient,
- upward and/or downward advective liquid flow, and
- upward diffusion of nuclides within liquid phase driven by concentration gradient.

The timing and magnitude of precipitation and evapotranspiration are major factors controlling water movement in the vadose zone. The sole source of water in the system is precipitation. High evapotranspiration removes much of the precipitation entering the system before it can infiltrate to significant depths. The dry conditions that prevail most of the time in the near surface lead to extremely low unsaturated hydraulic conductivities and little movement of moisture. The natural hydrologic conditions at the Area 5 RWMS act to reduce the potential for radionuclide release and transport.

1.1 SCREENING OF HYDROLOGIC PROCESSES

This section describes the results of a preliminary evaluation of the significance of hydrologic processes. It is based on site characterization data and results from analogous desert sites.

1.1.1 Precipitation

Precipitation is the sole source of water entering the vadose zone. The duration and intensity of precipitation is highly variable in Frenchman Flat, ranging from short, intense isolated thunderstorms in the summer to longer lower intensity events in the winter.

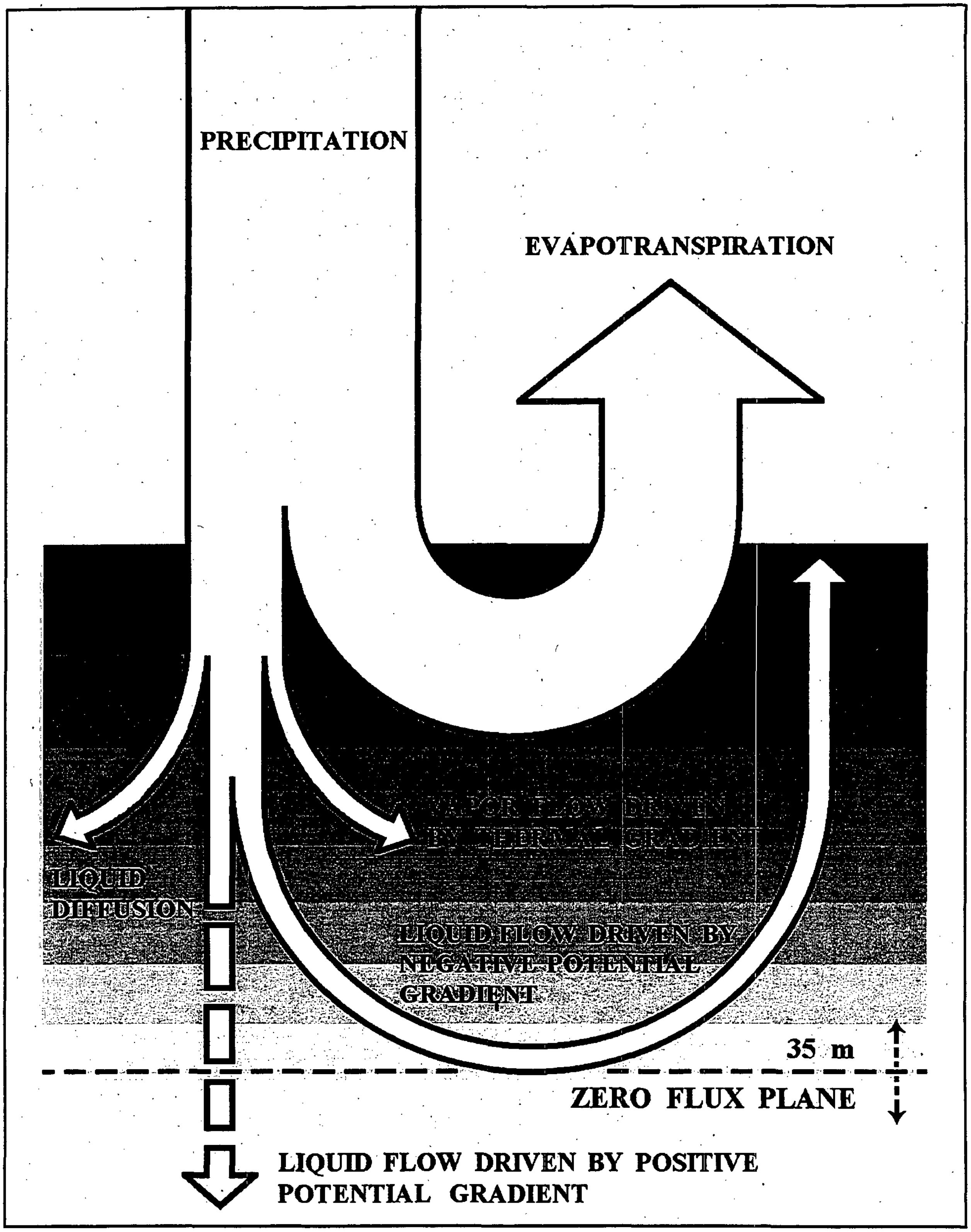


Figure D.1 - Potential hydrological and meteorological processes affecting water movement in the vadose zone at the Area 5 RWMS. (Arrows depict direction of flow and gross relative magnitude only, not drawn to vertical scale).

The longest record of daily rainfall near the Area 5 RWMS covers a 31-year period, from 1963 to 1994, recorded by the National Oceanographic and Atmospheric Administration (NOAA) at Well 5B (Table D.1), of which the most recent 14 year period is available on electronic media. Over this period, the mean annual rainfall was 12.55 cm. The annual total was highly variable ranging from a minimum of 2.90 cm to a maximum of 23.42 cm. Figure D.2 shows the 14 year period used in hydrologic modeling in Section 2.4.

1.1.2 Evapotranspiration

Evapotranspiration (ET) includes evaporation from bare soil, due to solar radiation and transpiration of water from the subsurface into the atmosphere via vegetation. Evapotranspiration values vary widely, depending upon the species of vegetation, soil structure, temperature, and water chemistry. Evapotranspiration can be differentiated into either potential evapotranspiration (ET_{POT}) or actual evapotranspiration (ET_{ACT}). ET_{POT} is that amount of evaporation that would arise from a soil if enough water were always available to meet the evaporative demand. As a soil dries, it becomes increasingly difficult to transmit water from the wetter areas within the soil profile to the surface, where evaporation takes place. This inhibits the evaporative process, making the actual evapotranspiration, ET_{ACT}, considerably less than ET_{POT}. Evapotranspiration may be determined either from an energy balance analysis or by empirical calculations (Monteith et al. 1990; Jensen et al. 1990). One measure of ET_{POT} is pan evaporation.

At the Area 5 RWMS, ET_{POT} varies as a result of seasonal climatic conditions, cloud cover, and precipitation. Due to high average temperatures, low humidity, and high rates of ground surface insolation on the NTS, ET_{POT} is relatively high and ranges from 169.8 to 178.5 cm yr^{-1} in Area 6 (French, 1993). Since the elevation of Area 6 is greater than that of the Area 5 RWMS, using ET_{POT} values from Area 6 for the RWMS is very conservative. The annual value of ET_{POT} is quite high compared to the mean annual value for precipitation (170 cm versus 12 cm). Accordingly, the vast majority of the precipitation falling on the Area 5 RWMS should be lost to the atmosphere either before it has had the time to infiltrate into the ground surface, or soon afterwards.

Experimental and modeling studies in the similar climate of the Chihuahuan Desert of Texas has also shown shallow and rapid recycling of precipitation (Scanlon, 1994; and Scanlon and Milly, 1994). These authors showed that the vast majority of movement of both liquid and water vapor was limited to the upper 30 cm of soil.

Table D.1. Monthly precipitation (cm) for the period from January 1963 to December 1993 at Frenchman Flat (Well 5B).

Table D.1. continued.

YR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
90	1.803	0.381	0.254	0.559	0.965	0.229	1.245	0.864	0.838	0.025	1.143	0.051	8.357
91	0.559	1.245	1.803	--	0.381	0.051	0.254	0.406	1.397	0.432	0.051	1.346	7.925
92	0.813	3.327	3.835	0.051	0.762	--	0.584	0.102	--	1.880	--	2.743	14.097
93	5.029	6.807	1.397	0.025	--	0.254	--	0.635	--	0.508	0.914	1.143	16.713
MEAN	1.575	1.499	1.397	0.737	0.762	0.305	1.067	1.346	0.940	0.635	1.092	1.219	12.548
MIN	--	--	--	--	--	--	--	--	--	--	--	--	2.896
MAX	5.029	7.087	6.096	4.216	5.004	2.235	6.655	9.500	5.486	2.870	3.531	5.791	23.419
SD	1.575	1.981	1.626	1.016	1.016	0.483	1.448	2.032	1.321	0.787	1.168	1.524	5.410

† "--" indicate zero precipitation.

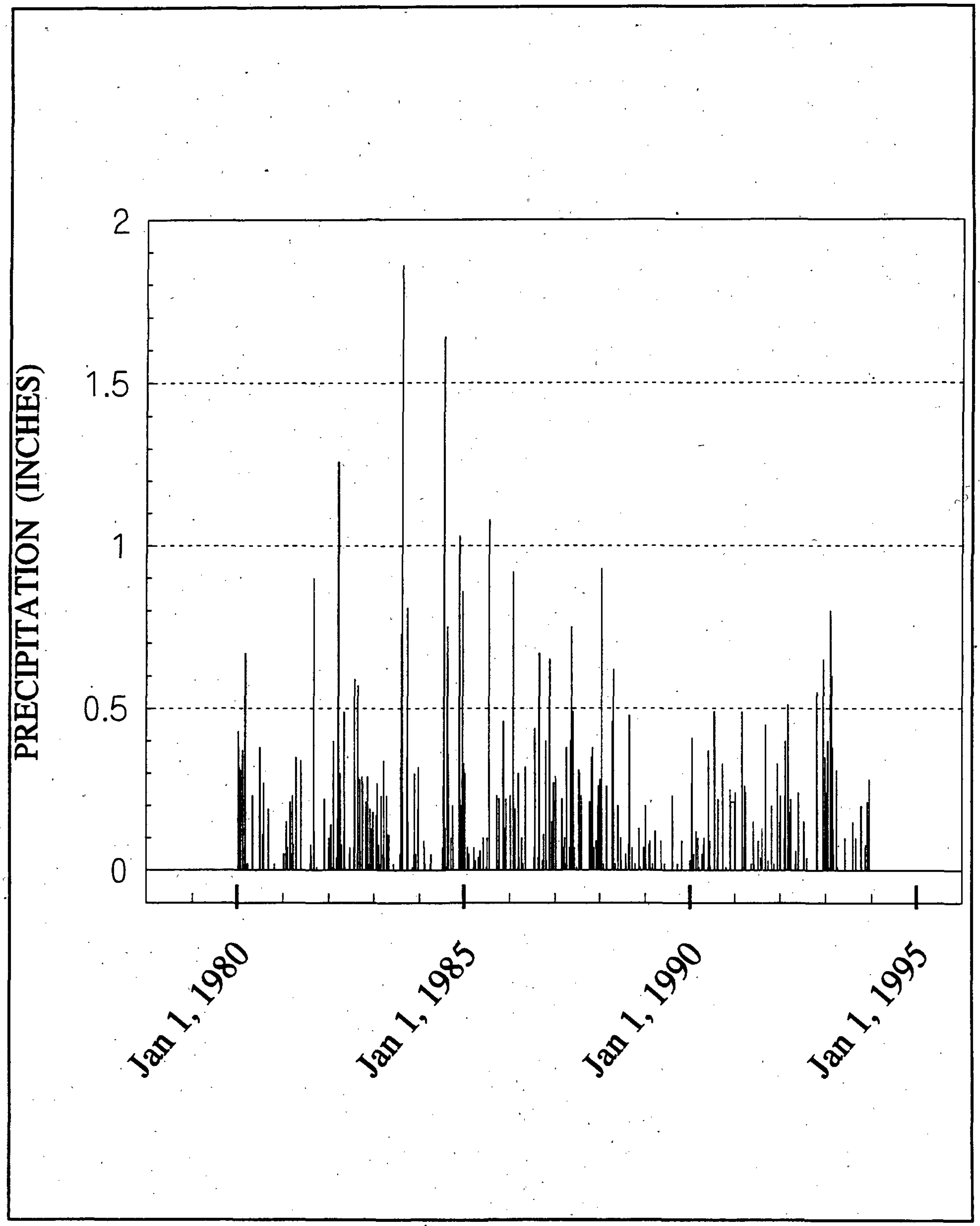


Figure D.2 - Daily precipitation data collected for Well 5B at Frenchman Flat from 1980 to

Since the climatic conditions of precipitation, evaporative demand, and the soil conditions of the Chihuahuan Desert are comparable to that at the NTS, Scanlon and Milly's results should also be applicable to the Area 5 RWMS. This conclusion is supported by matric potential profiles measured at the Area 5 RWMS (REECo, 1993a, 1993b, 1993c).

Under the current hydrologic regime, most precipitation is recycled back into the atmosphere soon after landfall due to the high evaporative demand of the arid climate. Therefore, there is very little water available after evapotranspiration for downward infiltration into the RWMS.

Estimation of the Annual ET at the Area 5 RWMS

To understand the significance of ET in the near surface alluvium, it is desirable to know ET_{ACT} on an annual basis. For this reason, and as part of the ongoing site characterization study, a water balance monitoring program has been initiated using two weighing lysimeters to measure ET_{ACT} at the Area 5 RWMS. The two lysimeters are currently undergoing calibration. The first water balance data report with a full year of data should be available by January 1996. Since these data were not available for this performance assessment, Penman's (1948) combination equation was used to estimate the daily ET_{POT} throughout the year at the RWMS. The Penman equation is sometimes referred to as the "energy balance plus heat and mass transfer" method. The method estimates the energy balance at the soil surface, taking into account heat and mass transfer from the soil by water vapor and advection.

The Penman equation estimates the maximum ET_{POT} at soil surfaces from the temperature and vapor pressure of the evaporating surface, the difference in energy flux at the surface, atmospheric pressure, and wind speed. The micrometeorology station at the Area 5 RWMS has the capability to record these variables. A modified form of the Penman equation (Jensen et al. 1990) is:

$$\lambda E_{to} = \frac{\Delta}{\Delta + \gamma}(R_n - G) + \frac{\gamma}{\Delta + \gamma} 6.43\, W_f(e_z^0 - e_z) \quad (1)$$

where:

E_{to}	=	potential evapotranspiration,
λ	=	latent heat of vaporization, (kJ kg^{-1}),
Δ	=	slope of saturation vapor pressure curve, $(4098\ e°)/(T+237.3)^2$, Tetens (1930) and Murray (1967),
T	=	dry bulb temperature, (C°),

$e°$	=	saturation vapor pressure, (kPa),
γ	=	psychrometric constant, $(C_p P)/(0.622\ \lambda)$, (kPa $°C^{-1}$),
C_p	=	specific heat of moist air at constant pressure, (1.013 kJ $kg^{-1}°C$),
P	=	atmospheric pressure, (kPa)
R_n	=	net radiation, (MJ $m^{-2}\ d^{-1}$),
G	=	average daily sensible heat flux to the soil, (MJ $m^{-2}\ d^{-1}$),
$(R_n - G)$	=	difference between incoming solar radiation and outgoing long-wave radiation from the soil surface,
W_f	=	linear wind coefficient or function,
$e°_z$	=	saturation vapor pressure over water, (kPa),
e_z	=	actual vapor pressure at z level above ground surface, (kPa), and
$(e°_z - e_z)$	=	vapor saturation deficit.

The linear wind coefficient or wind function is given by:

$$W_f = (a_w + b_w u_2) \tag{2}$$

where: $R_n > 0$	$a_w = 0.27$ and $b_w = 0.526$	
$R_n \leq 0$	$a_w = 1.14$ and $b_w = 0.401$ (Frére and Popov, 1979), and	
u_2	= wind speed at 2 m above ground surface, (km d^{-1}).	

The potential ET at the Area 5 RWMS was estimated using the modified Penman equation and data collected at the micrometereorolgy station. Since the micrometeorology data set available at the time of analysis was limited to 211 days (from January 1, 1993 through July 30, 1993), the ET_{POT} was calculated for roughly half a year through the summer solstice on June 21. The data show a consistent rise in the evaporative demand from the winter months into the summer. A fourth-order polynomial was fit to the data to smooth the scatter within the individual data points and provide a smooth curve relating the evaporative demand to the time of year (Figure D.3). The fitted curve for the first 6 months of the year, where the independent variable x denotes day of the year (January 1 = 1, January 2 = 2, etc.), was:

$$ET_{pot} = -2.287E\text{-}8x^4 + 7.580E\text{-}6x^3 - 6.430E\text{-}4x^2 + 0.0450x + 0.978. \tag{3}$$

The coefficient of determination (r^2) for this model was 0.84. The ET_{POT} for the rest of the cycle, from the summer solstice through the end of December, was approximated by reflecting the curve (mirror image) about the summer solstice, which yielded a plausible set of values for the entire year.

1.1.3 Vapor Flow Driven by Thermal Gradient

Water transport by vapor flow at the Area 5 RWMS involves vertical diffusive fluxes driven by vapor pressure gradients. These vapor pressure gradients may be caused by (1) spatial variations of water content, which are associated with the matric potential gradient, $(d\psi/dz)$, which influences the vapor pressure driving force $(d\rho_V/dz)$; and (2) surficial warming of the soil due to incident solar radiation, which can produce a thermal gradient (dT/dz) driving

(non-isothermal), and are represented mathematically as:

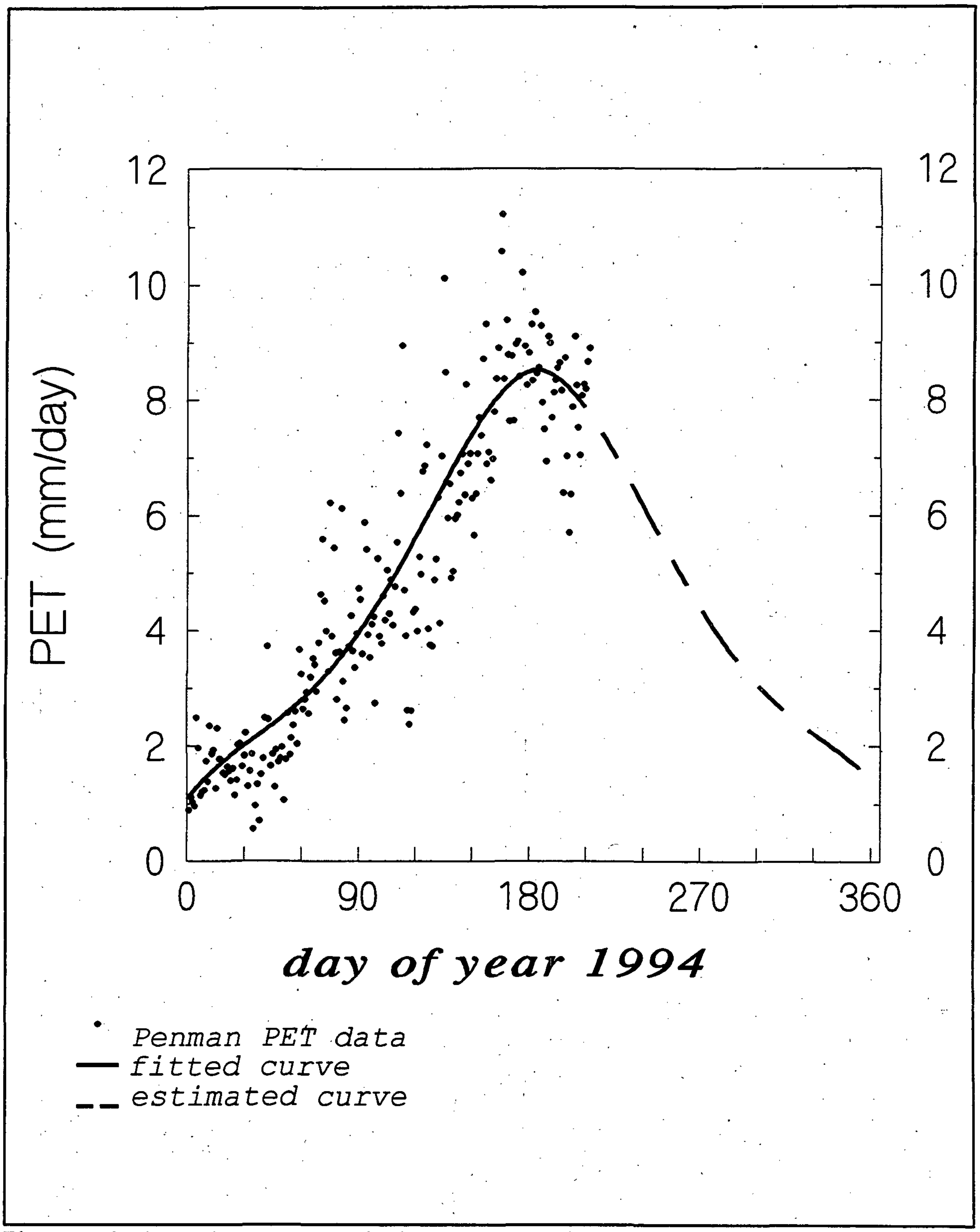


Figure D.3 - Potential evapotranspiration calculated with a modified form of the Penman equation (Jenson et al. 1991) using micrometeorological data collected at the Area 5 RWMS.

below the surface. In the winter, the thermal gradient is upward, and the tendency for vapor movement is up and out of the soil into the atmosphere. This cyclical behavior also occurs on a daily basis as well. This conceptual model of vapor movement is supported by Scanlon and Milly (1994). They showed that although both thermal and isothermal vapor fluxes are small below 30 cm, water movement in the Chihuahuan Desert was dominated by the thermal vapor flux term of Equation 4. The magnitude of thermal vapor flux in the subsurface was extremely small, and ranged from 1.5 mm yr^{-1}, at a depth of 0.5 m, to 0.17 mm yr^{-1}, at a depth of 5 m. The high degree of climate-induced surface heating tended to cause downward movement of soil water vapor from the surface after each rainfall. The vapor flow quickly died away once the water content was removed from the near surface.

Since Frenchman Flat and the Chihuahuan Desert have similar climates, one would expect Scanlon and Milly's findings to hold at the Area 5 RWMS as well. Therefore, it is not reasonable to consider vapor flow as an important mechanism for water movement in the vadose zone.

1.1.4 Advective Liquid Flow

Advective movement of water is driven by a difference in the matric potential gradient at various locations within the soil profile. The rate and direction of movement depends on both the magnitude and sign of the total gradient, as well as the hydraulic conductivity ($K(\theta)$) at the prevailing water content (θ) (i.e., the drier the soil, the less the hydraulic conductivity). Figure D.1 shows two separate arrows for advective transport of liquid; LIQ_{-POT} and LIQ_{-POT}. LIQ_{-POT} reflects the upward flow of liquid driven by a negative water potential (matric) gradient ($-d\psi/dz$), which results from the high evaporative demand at the land surface. This upward flux normally dominates under ambient conditions at the Area 5 RWMS. LIQ_{-POT} indicates a downward direction of liquid flow driven by a positive water potential gradient ($d\psi/dz$), which might occur after infrequent infiltration events.

1.1.4.1 Upward Advection Driven by Potential Gradient

Since the matric potential profile data from the Science Trench Boreholes (REECo, 1993c) and the Pilot Wells (REECo, 1993b) show a strong upward (negative) gradient from a depth of 30 to 35 m (the zero flux plane), water will tend to move upward in this zone. Dissolved nuclides could conceivably travel upward with the water and eventually be transported to the surface or to the root zone. Although the alluvium's low water content will cause the magnitude of flux to be very small, the velocity of liquid water movement from the waste cell to the surface and associated travel time can be estimated.

Method of Analysis

The mean travel time for upward advection was determined by discretizing the smoothed water potential profile and using a step-wise constant approximation for $d\psi/dz$. Isotropic conditions can be assumed (REECo, 1993c; Istok et al. 1994; Sully et al. 1993).

Darcy's law for isotropic vertical unsaturated flow,

$$q_z = -K(\theta)\left[\frac{d\psi}{dz} + 1\right] \tag{5}$$

may be used to calculate the velocity (v) of the pore fluid ($v=q_z/n$, where n is the water-filled porosity). Since upward flow only occurs within the top 30 to 35 m of alluvium, data from the Science Trench Boreholes (REECo, 1993c) was used rather than from the Pilot Wells (REECo, 1993b). Using a mean smoothed matric potential profile of the top portion over all of the Science Trench Boreholes (Figure D.4), the slope of the profile $d\psi/dz$ was discretized into segments (Figure D.5). A step-wise approximation of the Darcian flux along the profile was generated by assuming that the value for $d\psi/dz$ is constant within each segment.

The unsaturated hydraulic conductivity was estimated using the geometric mean soil-water characteristic data obtained from the Science Trench Boreholes (Figure D.6, D.7, and Table D.2). A relation between water content and matric potential was obtained by fitting water retention data to a model by van Genuchten (1978, 1980) of the form:

$$\theta_v = \theta_r + (\theta_s - \theta_r)\left[1 + (-\alpha\psi)^n\right]^{-m} \tag{6}$$

where θ_v is the volumetric water content (cm^3/cm^3), θ_s is the saturated volumetric water content, θ_r is the residual volumetric water content, ψ is the matric potential (cm), and α, m, and n are curve fitting parameters. The unsaturated hydraulic conductivity function K(θ) was derived by substitution of the van Genuchten model parameters into the Mualem (1976) model for unsaturated hydraulic conductivity. Doing this we obtain:

$$K(\theta) = K_s S^{1/2} \left[1 - \left(1 - S^{1/m} \right)^m \right]^2 \tag{7}$$

where K_s is the saturated hydraulic conductivity and S is the effective saturation as defined by:

$$S = \frac{(\theta - \theta_r)}{(\theta_s - \theta_r)} \tag{8}$$

The mean matric potential within each segment was translated into water content using Equations 7 and 8 (Figure D.6).

The average travel time for liquid water to flow from 2.4 meters below the soil surface (top of the emplaced waste) to the soil surface was calculated using the computer programs UPPROF and UPPFLOW. UPPROF calculates water potential as a function of depth below the surface, using an equation fitted to the Science Trench Borehole data in Figure D.4. A table of water potential values was calculated, which was used as input for the program UPFLOW.

UPFLOW sums the travel times for liquid flow through each segment, from any point within the profile (Figure D.5 and Equation 5), to determine the total travel time for a given

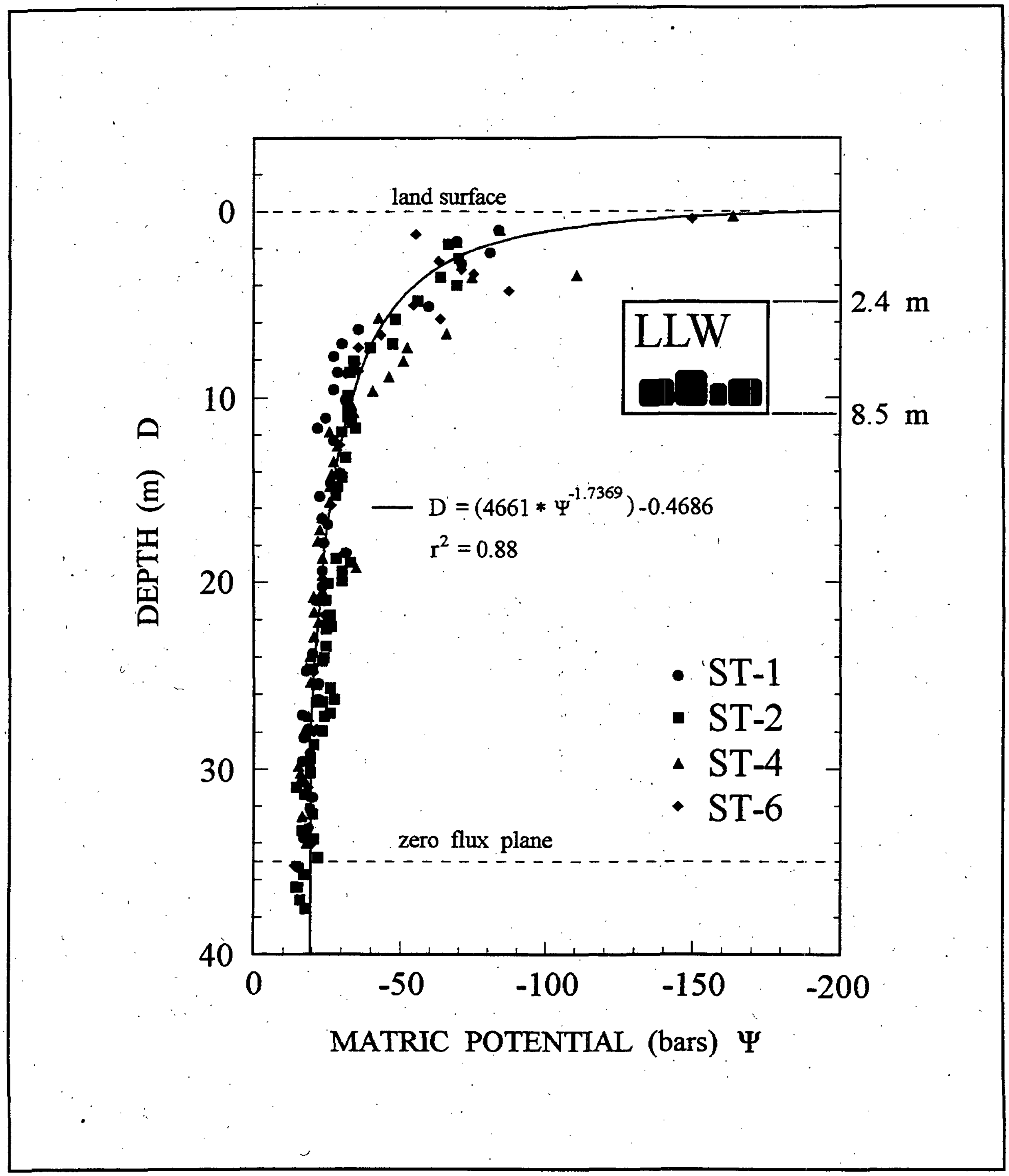


Figure D.4 - Smoothed average depth profile (modified power function) calculated from near surface matric potential data. Surface data was collected for alluvium from the Science Trench Boreholes (REECo, 1993c). Diagram of a shallow land burial low-level waste cell at the Area 5 RWMS is included to indicate the average vertical dimensions of a generic waste cell with respect to the land surface (including a temporary 2.4 m cap of native alluvium).

(m)

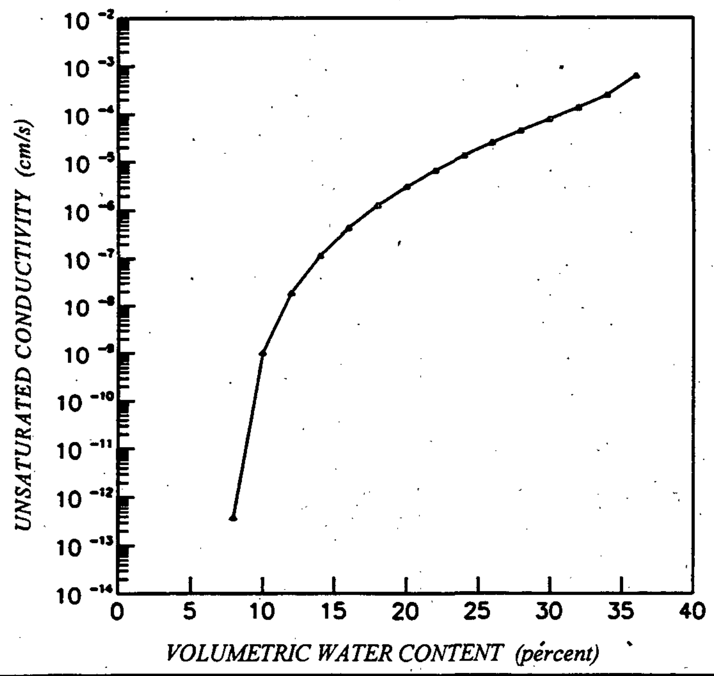


Figure D.6 - Mean soil moisture characteristic curve for alluvium from the Science Trench Boreholes.

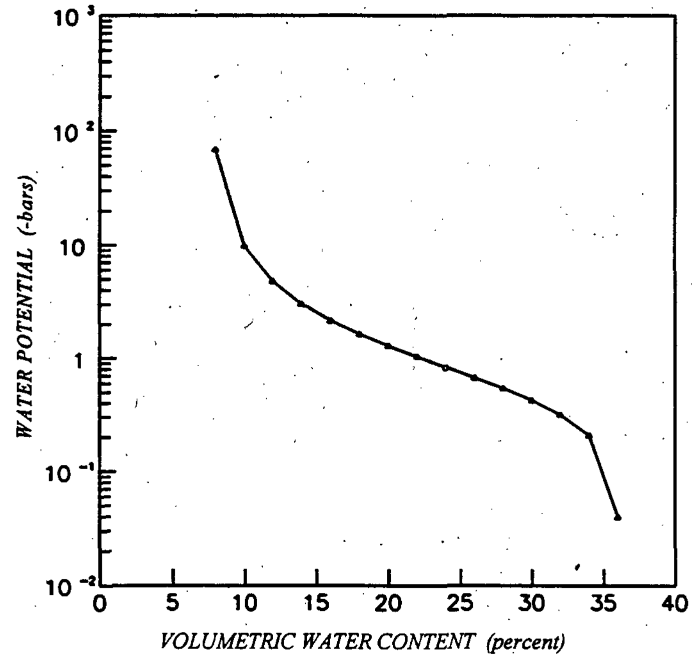


Figure D.7 - Mean soil moisture characteristic curve for alluvium from the Science Trench Boreholes.

Results for Upward Advective Liquid Flow

The calculations described above suggest that the total time for liquid water to travel 2.4 m up from the top of the emplaced waste to the land surface (based on matric potential as the only driving force) is about 5×10^8 years (0.000048 mm yr^{-1}). The distance traveled in 10,000 years is estimated to be less than 1 cm. This extremely long travel time is the result of the very low water content in the alluvium. At the near surface, the alluvium is so dry that a continuous phase of liquid between grain boundaries is unlikely to exist, thus, the unsaturated hydraulic conductivity is extremely small. Based on these calculations, upward advection of contaminants is not expected to be a concern under the dry ambient conditions that occur most of the time in the vadose at the Area 5 RWMS. Radionuclides will travel negligible distances within 10,000 years and most will decay to insignificant levels before reaching the surface.

Table D.2. Descriptive statistics for hydraulic properties (fitted van Genuchten parameters) from all Science Trench Borehole core samples (UeST-1, ST-2A, ST-2, ST-4, ST-5, ST-6, ST-7), "min" and "max" are minimum and maximum, "mean" and "s" are, respectively, the geometric mean and arithmetic standard deviation (REECo, 1993c).

Statistic	θ_r (cm^3 cm^{-3})	θ_s (cm^3 cm^{-3})	α (cm^{-1})	n	K_{sat} (cm s^{-1})
Min	0.00	0.32	0.008	1.30	1.0×10^{-5}
Max	0.10	0.40	0.030	3.12	4.9×10^{-3}
Mean	0.075	0.361	0.019	1.831	7.4×10^{-4}
s	0.024	0.019	5.71×10^{-3}	0.529	8.7×10^{-4}
No. samples	18	18	18	18	186

1.1.5 Upward Diffusion of Nuclides Within the Liquid Phase Driven by a Concentration Gradient

The limited infiltration of water at the surface suggests the potential for upward diffusion of nuclides through the temporary 2.4 m cap to the surface. The movement of solutes in soil systems was recognized early on to be influenced by the moisture content of the soil as well as the concentration gradient (Heslep and Black, 1954; Stewart and Eck, 1958). This movement can be described by Fick's first law adapted for unsaturated media as:

$$F = -D(\theta)\frac{dC}{dx} \tag{9}$$

where the mass flux of diffusing substance (F) passing through a given unit area cross section per unit time is proportional to the concentration gradient (dC/dx) multiplied by the diffusion coefficient ($D(\theta)$). In porous media, the effective diffusion coefficient $D(\theta)$ becomes very small as the water content of the soil decreases because: (1) a continuous liquid phase to support diffusion is absent, (2) an increase of the viscosity of water near the grain boundaries, and (3) adsorption of the solute onto the grain boundaries themselves (Olsen et al. 1965).

Due to the non-linear nature of the diffusion coefficient, the magnitude of flux (F) is generally more strongly controlled by changes in the water content rather than concentration (Kemper and van Schaik, 1966). Because of the inherent experimental difficulties, unsaturated diffusion coefficients are rarely measured. One alternative to direct measurement is to approximate the parameter using the relationship found by Kemper and van Schaik (1966), who determined experimentally that the diffusion coefficient for chloride increased exponentially in water content as:

$$D(\theta)_{effective} = D \cdot a \cdot e^{b\theta} \tag{10}$$

where a and b are empirical constants determined for a silty clay loam. It is reasonable to assume that conservative solutes other than chloride will behave similarly. Kemper and van Schail's description of the diffusion coefficient could be combined with Fick's Law to determine the average mass flux of nuclides that might escape the waste cell. An analysis of this is not necessary, given the very low water content observed in the near surface alluvium. Because the upward diffusion in the alluvial pore spaces requires a continuous phase of liquid water in which to take place, diffusion will not yield any significant additional flux of nuclides away from the system under the present dry conditions. This conclusion is supported in the literature by studies involving Cl^- in Ca^{2+} saturated systems (Porter et al. 1960) where zero transmission was observed at water contents ranging from 0.077 to 0.155 in a loam soil. Since the average background water content of the alluvium at the RWMS is at most 0.10 to 0.12, diffusive transport of radionuclides is not expected.

1.1.6 Summary of Screening Analysis

A preliminary screening analysis of hydrologic processes affecting water movement in the vadose zone has been performed. The implications of these processes for radionuclide transport has been evaluated. Vapor fluxes at analog sites have been found to be negligible and it is assumed that this process is negligible at the NTS also. While a potential for upward advective flow exists, the prevailing dry conditions of the alluvium reduce hydraulic conductivities to such low levels that most radionuclides will decay before reaching the accessible environment. Upward diffusion is also not likely to be of any significance under ambient dry conditions. Because of the extremely dry nature of the alluvium and the prevailing climate at the Area 5 RWMS, liquid advection and diffusion are too small to significantly effect the movement of radionuclides out of the waste cells. Precipitation and ET are the only two hydrologic processes having a significant effect on the movement of water in the vadose zone.

2.0 TRANSIENT INFILTRATION MODELING

In the previous section, it was shown that under the conditions that prevail most of the time at the Area 5 RWMS, the alluvium is too dry to allow significant advection of moisture or diffusion of solutes. These conclusions were based on site characterization data that represent measurements collected at one point in time (steady-state assumption). Since precipitation and ET can vary, additional study of the transient effects of infiltration was required.

The screening done in the previous sections suggests that variable precipitation and evapotranspiration are the factors most likely to influence water-mediated radionuclide transport. The transient nature of these conditions required a numerical model capable of describing the temporal variations. Deterministic and stochastic-statistical approaches were evaluated.

2.1 THE DETERMINISTIC APPROACH TO TRANSPORT

The deterministic viewpoint is based on the assumption that transport can be completely described by a mathematical equation. The equation incorporates a number of characteristics such as pore space velocity, potential, concentration, density, hydraulic conductivity, and water content. These properties are assumed to be representative of the system as a whole on the scale of interest, and are either known or can be fully described in a functional form.

Major problems with the deterministic viewpoint for the Area 5 RWMS are: (1) our current understanding of the transport process in porous media is incomplete, making the microscopic velocity variations within the pore spaces, and molecular diffusion ($D_{diffusion}$), which arises due to concentration gradients. Since the effects of the processes are difficult to separate from one another, the diffusion-dispersion coefficient is often simply called the dispersivity. The second term on the left in Equation 11 accounts for changes in solute concentration due to advection of solute through the media. The third and fourth terms represent, respectively, radioactive decay or adsorption of the solute onto the aquifer matrix, and a source or sink term.

The advection-dispersion-reaction equation is difficult to solve for saturated media. Under unsaturated conditions, the equation's non-linear nature makes finding a solution even more difficult. Dispersivity is influenced by a number of factors including the velocity within the pores themselves, the position of the solute within the pore, and the pore size. There is a growing body of evidence that indicates that it is dependant on water content (Warrick, 1971; Kirda et al. 1974; Biggar and Nielsen, 1967). Under unsaturated conditions, the water-filled porosity is small and the actual pathways for solute transport become very tortuous (i.e., the tortuosity (ξ) is a function of water content). Most studies, however, have been done holding dispersion constant (Boast, 1973; Rubin and James, 1973; Cameron and Klute, 1977;

and Fried (1981) presented overviews of the scale problem associated with the determination of groundwater travel times and path. They both recognize that currently available models are inadequate for representing either the observable phenomena of transport or the role of scale effects in the determination of the dispersion-diffusion parameters.

One last problem with the application of the deterministic transport approach is how to handle the question of multi-process non-equilibrium sorption-desorption in unsaturated media. Recent studies have involved saturated systems (van Genuchten and Wagenet, 1989; Lassey, 1988; Brusseau et al. 1992), but not unsaturated ones.

Virtually no codes exist that address the various fundamental flaws in the mathematical description of the unsaturated transport process dealing with the scale, non-equilibrium sorption, and moisture content dependance of dispersivity. Models designed for use in determining transport in saturated systems may not be applicable for predicting the travel time and concentration of contaminants in unsaturated systems. Results from the application of such models should be approached with a great deal of caution This brings us to the second way of approaching solute transport, the stochastic-statistical approach.

2.2 THE STOCHASTIC-STATISTICAL APPROACH TO TRANSPORT

Since contaminant transport modeling has become an important part of the regulatory process for shallow land-fill disposal sites, analysis of the uncertainty of the input parameters has been recognized as increasingly important (Rubin and Dagan, 1992; Schanz and Salhotra, 1992). The prediction of travel times is frought with uncertainty, from undefined spacial variabilities of formation properties, to uncertainties in the flow model parameters themselves. For example, neglecting small profile heterogeneities can seriously overestimate the effective solute velocity (Russo et al. 1989). The stochastic-statistical approach was developed to address some of the parameter uncertainty involved in the modeling process.

Stochastic methods usually reformulate Equation 11 into a stochastic partial differential equation in which the boundary conditions, initial conditions, source/sink term, velocity particles of fluid travel through a porous system (Scheidegger, 1954; Day and Forsythe, 1957). More recently, stochastic continuum theory has been developed to describe dispersion and solute transport (Dagan, 1982; Dagan, 1986; Naft, 1990; Dagan et al. 1992; Rehfeldt and Gelhar, 1992).

The use of Monte Carlo techniques to describe the random nature of flow and transport variables has been perhaps one of the most promising approaches, especially in heterogeneous formations (Bellin et al. 1992). The principle is simple. Assuming that a particular parameter of interest (Z) is a stochastic process, one generates many simulated values of Z (realizations) based on its known probability distribution function and its covariance measured from field data. The flow equation is solved for each variation of Z, yielding an ensemble of possible solutions (Dagan, 1989; de Marsily, 1986). The main difficulty with the method is that it is extremely computationally expensive and although promising, the method has been used mainly as an experimental tool rather than as a general solution to the transport problem.

2.3 NUMERICAL MODEL SELECTION AND REASONING

Sections D.2.1 and D.2.2 outline the limitations of current state-of-the-art transport codes when applied to the unsaturated transport problem. Based on those arguments, it is reasonable to first determine whether there will be any moisture flow in or out of the waste cells due to transient infiltration events before attempting to model transport, since the use of transport calculations is unnecessary if there is no detectible unsaturated liquid flow.

In order to model unsaturated liquid flow, an unsaturated flow code was required that was capable of simulating transient infiltration arising from discrete precipitation events and a seasonal evapotranspiration rate. A one-dimensional analysis was deemed sufficient for the Area 5 RWMS because: (1) the site characterization data indicates that the hydrologic behavior of the alluvium is isotropic and homogeneous (Sully et al. 1993, Istok et al. 1994); and (2) the scale of the problem is such that precipitation and evapotranspiration occur over a

2.3.1 General Code Description

The UNSAT2 computer code was originally documented by Neuman et al. (1974) , and applied to various flow problems by Feddes et al. (1974), Kroszynski and Dagan (1975), Wei and Shieh (1979), and Zaslavsky and Sinai (1981). The model is intended for the simulation of partially or unsaturated flow in porous media, in either one or two dimensions.

The method of solution is based on a lumped-mass Galerkin finite element scheme. Quadrilateral and triangular elements, which can be generated with ease by a companion program named GRIDDER, created to facilitate the design and generation of two-dimensional finite element grids (Guzman, 1993), were utilized. The Galerkin method produces a set of simultaneous linear algebraic equations which are eventually solved for matric potential at all nodes at any given time, using a Gaussian elimination scheme specifically tailored for symmetric positive-definite banded type matrices. Due to the finite element method of domain discretization. UNSAT2 can accommodate irregular boundaries and anisotropic layers

x	=	width dimension,
$C(\psi)$	=	specific moisture capacity $= \partial\theta/\partial\psi$,
θ	=	volumetric water content,
S	=	source/sink term,
S_s	=	specific storage, and
β	=	0 in unsaturated zone, 1 in saturated zone.

Equation 12 states that the amount of liquid advection and/or drainage into or out of a discrete elementary volume of porous material due to a matric gradient, is equal to the change in storage within the volume, plus or minus additional outside sources or sinks. The specific storage is assumed constant in time in saturated regions, and zero in unsaturated flow regions, since only in saturated systems is storage effected to any degree by compressibility effects. Standard practice dictates that the water potential is positive in saturated zones and negative (matric potential) under unsaturated conditions. Hysteresis in either the moisture characteristic curve, $\theta(\psi)$, or the specific moisture capacity, $C(\psi)$, is not considered in the code.

2.3.3 Code Requirements

UNSAT2 was originally developed for use on an IBM system, and documented for a CDC 6600/7600 mainframe system. The program has been written in standard FORTRAN-77. Computer memory and peripheral disk storage requirements are a function of the size of the problem (i.e. number of defining nodes and/or elements). Due to the implementation of the finite element method, large amount of core memory are not normally required for successful simulations.

Initial testing revealed that a 7000 node 2-D simulation is possible on an IBM 80486-66 MHz PC with 16 Mb memory utilizing a 32-bit FORTRAN compiler operating under the WINDOWS© 3.1/DOS operating system. Since the performance assessment simulations were one-dimensional, the PC provided more than enough resources to accomplish the modeling task.

The input data file required by UNSAT2 is defined by a number of lines in sequential order and fixed format. Various lines provide information for the simulation title, output control, general simulation control data (number of nodal points, maximum number of iterations, simulation time, step size, etc.), porous material properties (porosity, hydraulic properties), and nodal point and element information (type of boundary conditions, etc.).

Initial conditions are satisfied by providing the matric potential at every node within the domain, since $\psi(\theta)$ is a single-valued function of water content. Hydraulic properties must be specified for each material if the simulation involves a heterogenous system. These include saturated hydraulic conductivity, specific storage, porosity, relative conductivity as a function of moisture content, and matric potential as a function of water content. Functional relationships supplied as a user option within the program include the van Genuchten model, the Gardner model, the Garner-Russo model, or a user defined formulation.

2.3.4 Output Options

The current version of UNSAT2 provides an output file containing the x, y, z coordinates, matric potential, nodal number, and total head values at the end of the simulation. The plotting program used, TECPLOT©, needed input in a different format. Thus, several modifications were added to the code to provide input for TECPLOT©. In particular, a new subroutine called UNPLOT was added to provide a real time visual interface to UNSAT2 when one-dimensional simulations were performed. UNPLOT allows the user to observe the evolving matric potential and water content profiles and iteration process during the simulation. Additional segments of code were added to the main program and to the subroutines MOIST and FEM to allow the user to output matric potential and moisture content versus the nodal coordinate system into an output file, suitable for use as an input file for the plotting program TECPLOT©.

2.3.5 Numerical Code Verification

A distinction must be made between verification and validation as they apply to mathematical models. Since some degree of ambiguity concerning the definition and implementation of these concepts exists, definitions are provided.

Verification

The term verification refers to the degree to which a computer code can accurately reproduce or reflect the mathematics used to describe the natural phenomena being simulated, not the phenomena itself. Generally, a mathematical model is considered verified when the results from a model can be shown to be accurate approximations to exact analytical solutions, even if the exact analytical solution does not reproduce the natural phenomena itself. Thus, verification is simply a test to determine if the mathematical representation within the model is sound, and error free. Validation, on the other hand, has been defined by various authors as either (1) "assurance that a model, as embodied in a computer code, is a correct representation of the process or system for which it is intended" (USNRC, 1984), or as (2) "a process whose objective is to ascertain that the code or model indeed reflects the behavior of the real world" (USDOE , 1986).

To gain assurance that the numerical code in UNSAT2 could accurately reproduce the underlying mathematics of Richard's equation (Equation 12), a comparison of the solution obtained from UNSAT2 for a transient problem was compared to the exact analytic solution presented by Yeh and Srivastava (1991). The solution starts with Richard's equation, given one-dimensional vertical flow in a homogeneous soil, which can be expressed as:

$$\frac{\partial}{\partial z} \cdot \left(K(\psi) \cdot \frac{\partial(\psi + z)}{\partial z} \right) = \frac{\partial \theta}{\partial t} \tag{13}$$

The hydraulic properties can be described by the Gardner model (Gardner, 1958):

$$K(\psi) = K_s e^{\alpha\psi}$$
$$\theta = \theta_r + (\theta_s - \theta_r) e^{\alpha\psi} \tag{14}$$

where K_s is the saturated hydraulic conductivity, θ_r is the residual moisture content, θ_s is the saturated moisture content, and α is a soil pore-size distribution parameter.

Yeh and Srivastava linearized Equation 13 to obtain:

$$\frac{\partial^2 K(\psi)}{\partial z^2} + \alpha \frac{\partial K(\psi)}{\partial z} = \frac{\alpha (\theta_s - \theta_r)}{K_s} \frac{\partial K(\psi)}{\partial t} \tag{15}$$

Dimensionless parameters can be defined and Equation 15 solved through a Laplace transform to yield an analytical expression for unsaturated hydraulic conductivity such that when substituted into the constitutive relations in Equation 14 yielded water content with depth over time. The dimensionless parameters (denoted *) were:

$$z_* = \alpha z \quad \text{so that} \quad L_* = \alpha L$$

$$K(\psi)_* = \frac{K(\psi)}{K_s} \tag{16}$$

$$q_A^* = \frac{q_A}{K_s} \qquad q_B^* = \frac{q_B}{K_s}$$

$$t_* = \frac{\alpha K_s t}{(\theta_s - \theta_r)} \tag{17}$$

where L_* is the depth to the water table, $\psi_o = 0$ is the prescribed matric potential at the water table, q_A* is the initial flux at the soil surface which, along with ψ_o, determines the initial matric distribution in the soil, and q_B* is the prescribed flux at the soil surface for time greater that zero.

The initial and boundary conditions were:

$$K(z,o) = q_A - (q_A - e^{\alpha\psi_o})e^{-z} = K_O(z)$$

$$K(0,t) = e^{\alpha\psi_o} \tag{18}$$

$$\left[\frac{\partial K}{\partial z} + K\right]_{z=L} = q_B$$

After taking the Laplace transform, a general analytic solution, subject to the boundary condition shown in Equation 18, was obtained using a MATHCAD spreadsheet (version 4.0 for Windows©). The solution is:

$$K(\psi)_* = q_B^* - (q_B^* - e^{\alpha \psi_o}) e^{-z} - 4(q_B^* - q_A^*) \cdot e^{(L_* - z_*)/2)} e^{-t_*/4} \sum_{n=1}^{\infty} \frac{\sin(\lambda_n z_*) \sin(\lambda_n L_*) e^{\lambda_n^2 t}}{1 + (L_*/2) + 2\lambda_n^2 L_*} \tag{19}$$

where $\{\lambda_i\}$ are the values of the positive roots of the characteristic equation:

$$\tan(\lambda L) + 2\lambda = 0 \tag{20}$$

A one-dimensional unsaturated flow simulation was performed with UNSAT2 for a 100 cm long soil column in which the hydraulic properties are described by the Gardner exponential model (Gardner, 1958). The parameters used in the simulation are presented in Table D.3. The UNSAT2 results were compared with the analytical solution obtained as described above. The UNSAT2 results and the analytical solution were found to be in excellent agreement (Figure D.8).

Validation

Regulatory considerations require an adequate description of phenomena for a given purpose, in this case, to provide reasonable assurance of compliance with the performance objectives. However, the validation of performance assessment models is ultimately a site-specific issue. Thus, the goal of validating a model should not be viewed from the framework of providing a number of laboratory or field test cases. Rather, it should be viewed as the collection of sufficient evidence supporting the contention that the model is able to simulate behavior of the real system and satisfy the regulatory purpose (Davis et al. 1991). To this end, field studies of near-surface water fluxes may someday be used.

Only through site characterization and monitoring, over an extended period of time, can sufficient confidence be gained that the model reflects the real site over a broad range of circumstances. Because of the site-specific nature of this process, validation of the UNSAT2 code is not yet possible due to unavailability of relevant data. When enough data become available for the environmental conditions at the RWMS, it will be possible to validate the code against a range of conditions.

However, the code has been validated numerous times at other locations. The reader is referred to the UNSAT2 manual (Davis and Neuman, 1983) for specific instances in which the UNSAT2 simulation results were compared to laboratory and field data. In particular, the code was validated for two laboratory experiments involving drainage from a one-dimensional column experiment, and a two-dimensional flume test (Skaggs et al. 1970; Duke, 1973; and Hedstrom et al. 1971); and one two-dimensional field scale study (Neuman et al. 1974) which investigated the water loses due to evapotranspiration and leakage to a lower aquifer on a potato field in the Netherlands. All three simulations essentially agreed with field and/or laboratory observations.

2.4 MODEL ASSUMPTIONS AND PARAMETERS

The transient modeling case was developed to describe the hydrologic environment in the near surface of the Area 5 RWMS under typical atmospheric conditions involving transient infiltration arising from time varying precipitation and variable seasonal evapotranspiration. The assumptions and parameters used in the numerical model are described below. This modeling case was analyzed to determine if transient infiltration could lead to wetter conditions in the vadose zone that would allow upward advection or diffusion to precede at significant rates.

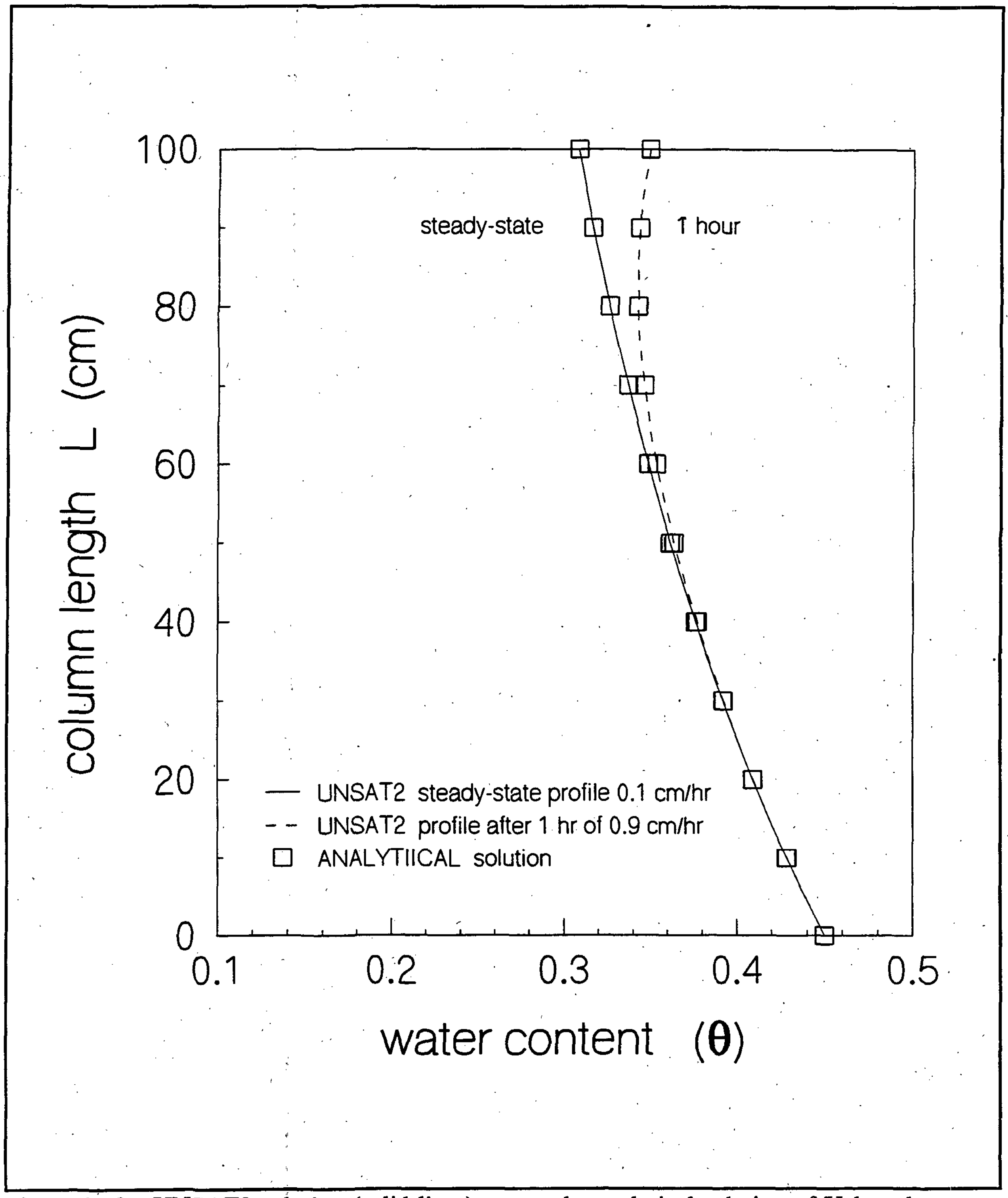


Figure D.8 - UNSAT2 solution (solid lines) versus the analytical solution of Yeh and Srivastava (1991) (boxes) for a wetting profile simulation for a 100 cm long soil column with a water table at the bottom, (102 nodal points, 50 elements, 100 max iterations, 0.25 initial time interval, 0.05 min time interval, 1.1 multiplier, 0.1 max iteration error).

2.4.1 Hydraulic Character of Alluvium

The following assumptions were made about the hydraulic character of the alluvium.

- The near surface is composed of alluvial deposits that are lithologically and mineralogically homogeneous. The hydrologic properties of the alluvium are also homogeneous and isotropic. This includes porosity (n), saturated hydraulic conductivity (K_{sat}), moisture retention ($\psi(\theta)$), and unsaturated hydraulic conductivity ($K(\psi)$).

- Water content of the alluvium is very low near the surface and increases only slightly with depth (from 5 percent at the surface to about 10 percent at a depth of 37 m) according to a smooth function as indicated by the Science Trench Borehole data (Figure D.4).

- Liquid flow is the only process of hydrologic consequence, and it occurs only in the vertical direction.

2.4.2 Model Boundary Conditions

The following time dependant boundary conditions were assumed. The simulation was performed using the longest record of tabulated daily precipitation data available for the Area 5 RWMS, a 14-year record collected within Frenchman Flat at Well 5B (Table D.1). Daily variation in evapotranspiration was estimated in Section D.1.1.2 from a modified form of the Penman equation (Jensen et al. 1990).

Since the simulation is one-dimensional in the vertical direction, the boundary conditions both at the soil surface and at depth were specified. The soil surface boundary condition was variable, i.e., the upper boundary condition was changed every 24 hours. The magnitude of either evaporation or infiltration occurring at the nodes along the soil surface was a function of the water content history in the soil and the weather conditions each day during the 14-year simulation. Daily data were used, since the actual rate of evaporation each day may be limited by the ability of the soil to transmit water upward to the surface. Conversely, the actual rate of infiltration may be limited by the infiltration capacity of the soil.

The simulation began with daily rainfall data from January 1, 1980 and ended with daily data from December 31, 1993. Rainfall was modeled as a 24-hour average, in which accumulations over each 24-hour period were transformed to a flux rate. On days in which there was no precipitation, the evapotranspiration rate, as calculated from the Penman equation, was averaged over each 24-hour period and applied as a negative flux at the surface nodes.

Within UNSAT2 the maximum rate of infiltration or evaporation was determined automatically by the program according to the following requirements (Hanks et al. 1969; Davis and Neuman, 1983; Davis and Neuman, 1983):

$$\left| K^r \sum_{i=1}^{3} \left(\sum_{j=1}^{3} K_{ij}^{sat} \frac{\partial \psi}{\partial x_j} + K_{i3}^{sat} \right) n_i \right| \leq \left| E_s^* \right| \quad \psi_L \leq \psi \leq 0 \tag{21}$$

where:

K^r	=	relative hydraulic conductivity,
K_{ij}^{sat}	=	saturated hydraulic conductivity,
ψ	=	water potential,
ψ_L	=	minimum allowed water potential at the soil surface,
x_j	=	dimension (x=3 is the vertical),
n_i	=	ith component of normal unit vector, and
E_s^*	=	maximum prescribed surface flux (evaporation or infiltration).

The bottom boundary condition was set at the water table as a prescribed head condition (ψ=0).

2.4.3 Initial Conditions

The initial conditions assumed for the simulation include the water potential profile or water content distribution in the alluvium with depth. This condition was set equal to the smoothed average water potential profile shown in Figure D.4 from the Science Trench Borehole data (REECo, 1993c).

2.4.4 Model Domain Discretization

The one-dimensional domain was modeled with a 281 rectangular element grid network of 564 nodes. The domain discretization was very fine both at the soil surface (0.01 m) and at the water table, and expands to 2 m in the center of the domain.

2.4.5 Parameter Selection

The hydrologic parameters used in the simulation were derived from the Science Trench Borehole Report (REECo, 1993c). These data were chosen as representative of the system (deterministic best point-value estimate) because of the concentration of data focusing on the near-surface environment. These included the best geometric mean for saturated hydraulic conductivity (K_s), residual (θ_r) and saturated (θ_s) water content, and the van Genuchten fitting parameters alpha (α) and (n) for the average water characteristic curve. These values are summarized in Table D.4 and Figures D.6 and D.7. Since the alluvium can be treated hydrologically as an isotropic homogeneous medium (Sully et al. 1993; Istok et al. 1994), no layering was incorporated into the model.

Table D.4. Parameter values used for the transient infiltration model using the UNSAT2 flow code.

Parameter Description	Symbol	Value for Simulation
Saturated hydraulic conductivity	K_s	0.6390 m-dy^{-1}
Rainfall infiltration rate	-	variable - daily
Evapotranspiration rate	-	variable - daily
Pore size parameter	α	1.9 m^{-1}
van Genuchten parameter	n	1.831
Residual water content	θ_r	0.075
Saturated water content	θ_s	0.361
Number of nodes in grid	NUMNP	564
Number of elements	NUMEL	281
Nodal spacing	-	variable - 1 cm to 2 m
Simulation time	t	14 yrs

2.5 MODEL RESULTS AND CONCLUSIONS

The water content profile from the simulation was output every day in which the precipitation was greater than 1 cm, and at the end of every year as shown in Figure D.9. In general, two conclusions can be drawn from the results:

- The maximum depth of infiltration during the simulation was less than 0.5 m (0.20 to 0.25 m).

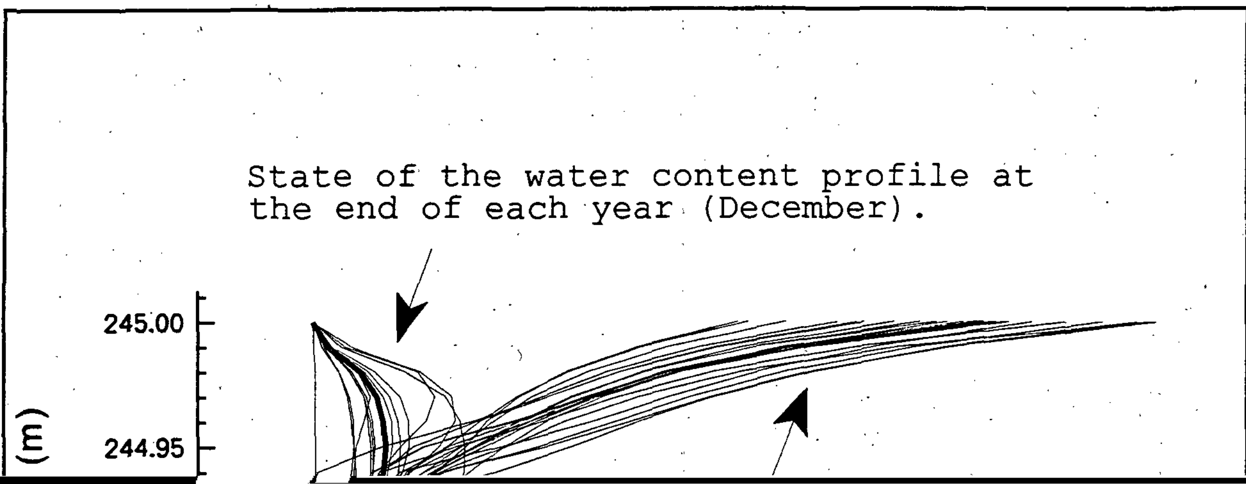
- The water content profile at each year's end shows that the evaporative demand was responsible for reducing the water content in the near surface during the year, and was the major factor in preventing water from moving deeper down the profile.

The simulated results show that under the conditions modeled (indicative of the current arid climate regime), most of the precipitation available for recharge is recycled back to the atmosphere because of the large daily evaporative demand at the surface. Even though the simulation was for a limited period of time (14 years), these results are a strong indication that water is unlikely to infiltrate to the depth of buried waste.

3.0 SUMMARY OF HYDROLOGY CONCEPTUAL MODEL AND ITS IMPLICATIONS FOR WATER-MEDIATED RELEASE OF RADIONUCLIDES

The hydrology conceptual model adopted for the performance assessment is based on site characterization data and modeling studies. A static model, based solely on site characterization data, proposed three zones of vertical water movement. All waste disposal cells at the Area 5 RWMS are located in Zone I, a 35 m thick surface zone where the potential for water movement is upward. Under the usual ambient conditions, the alluvium in Zone I is so dry that upward liquid advection occurs at negligible rates. The potential for diffusion of solutes is also eliminated in Zone I by the extremely dry conditions.

A transient modeling case was evaluated to assess the potential for rainfall to infiltrate to the depth of buried waste. Liquid advection and diffusion could occur at greater rates in Zone I after infrequent precipitation, if infiltrating rainwater were to penetrate to the depth of the waste. The modeling study suggests that the evaporative potential at the surface is so high that infiltrating water only penetrates a short distance before it is returned to the atmosphere.


State of the water content profile at the end of each year (December).
245.00
244.95
(m)

The hydrology conceptual model adopted for the performance assessment is quite similar to the model developed from site characterization data in Chapter 2. The only revision is that Zone I can be subdivided into two zones. In the near surface, perhaps to a depth of 0.5 m or less, there is a zone where conditions may change as rainwater infiltrates and is rapidly recycled to the atmosphere. The potential for water movement in this zone is normally upward, but may periodically reverse. Below this shallow surface zone from 0.5 m to 35 m, there is a zone where conditions are stable and not significantly influenced by precipitation events. The tendancy for water movement in this zone is upward. However, conditions are so dry in this zone that upward liquid advection and diffusion occur at negligible rates. The hydrology conceptual model suggests that there are no credible hydrologic processes operating at the depth of buried waste that could enhance the release of radionuclides.

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APPENDIX E

PARAMETERS AND INTERMEDIATE RESULTS FOR THE RELEASE AND PATHWAY SCENARIOS

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Table E.1. Radionuclide-specific, soil-plant dry mass concentration factors and transfer parameters for milk and beef.

Radionuclide	B_{iv}	B_{iv} Reference	F_m [a] (day kg^{-1})	F_b [a] (day kg^{-1})
Ac-227	3.5e-004	Bv from Baes et al., 1984	2.0e-005	2.5e-005
Am-241	4.0e-002	Romney et al., 1981	4.0e-007	3.5e-004
Am-243	4.0e-002	Romney et al., 1981	4.0e-007	3.5e-004
Ba-133	5.1e-002	CR from Ng et al., 1982	3.5e-004	1.5e-004
Bi-207	5.0e-003	Bv from Baes et al., 1984	5.0e-004	4.0e-004
C-14	5.5e+000	USNRC, 1977	1.2e-002	3.1e-002
Cl-36	7.0e+001	Bv from Baes et al., 1984	1.5e-002	8.0e-002
Cm-243	1.5e-005	Bv from Baes et al., 1984	2.0e-005	3.5e-004
Cm-244	1.5e-005	Bv from Baes et al., 1984	2.0e-005	3.5e-004
Cm-248	1.5e-005	Bv from Baes et al., 1984	2.0e-005	3.5e-004
Co-60	2.4e-001	CR from Ng et al., 1982	2.0e-003	2.0e-002
Cs-135	6.0e-002	Gilbert et al., 1988	7.0e-003	2.0e-002
Cs-137	6.0e-002	Gilbert et al., 1988	7.0e-003	2.0e-002
Eu-152	4.0e-003	Bv from Baes et al., 1984	2.0e-005	5.0e-003
Eu-154	4.0e-003	Bv from Baes et al., 1984	2.0e-005	5.0e-003
H-3	4.8e+000	USNRC, 1977	1.0e-002	1.2e-002
I-129	3.1e-001	CR from Ng et al., 1982	1.0e-002	7.0e-003
Ni-59	7.4e-002	CR from Ng et al., 1982	1.0e-003	6.0e-003
Ni-63	7.4e-002	CR from Ng et al., 1982	1.0e-003	6.0e-003
Np-237	1.9e+000	CR from Ng et al., 1982	5.0e-006	5.5e-005
Pa-231	2.5e-004	Bv from Baes et al., 1984	5.0e-006	1.0e-005
Pb-210	9.0e-003	Bv from Baes et al., 1984	2.5e-004	3.0e-004
Pd-107	4.0e-002	Bv from Baes et al., 1984	1.0e-002	4.0e-003
Pu-238	2.0e-003	Romney et al., 1981	1.0e-007	5.0e-007
Pu-239	2.0e-003	Romney et al., 1981	1.0e-007	5.0e-007

Table E.1. (Continued.)

Radionuclide	B_{iv}	B_{iv} Reference	F_m [a] (day kg^{-1})	F_b [a] (day kg^{-1})
Pu-240	2.0e-003	Romney et al., 1981	1.0e-007	5.0e-007
Pu-241	2.0e-003	Romney et al., 1981	1.0e-007	5.0e-007
Pu-242	2.0e-003	Romney et al., 1981	1.0e-007	5.0e-007
Ra-226	1.5e-003	Bv from Baes et al., 1984	4.5e-004	2.5e-004
Sm-151	4.0e-003	Bv from Baes et al., 1984	2.0e-005	5.0e-003

Table E.2. Fractional release rates for root uptake module.

Radionuclide	K_{r1}, yr^{-1} (waste to shallow soils)	K_{r2}, yr^{-1} (waste to subsurface soils)	K_{r3} yr^{-1} (subsurface soils to shallow soils)
H-3	4.26e-006	1.59e-006	6.45e-005
C-14	4.88e-006	1.82e-006	7.39e-005
Cl-36	6.21e-005	2.32e-005	9.41e-004
Ni-59	6.57e-008	2.45e-008	9.95e-007
Co-60	2.13e-007	7.95e-008	3.23e-006
Ni-63	6.57e-008	2.45e-008	9.95e-007
Kr-85	0.00e+000	0.00e+000	0.00e+000
Sr-90	3.11e-006	1.16e-006	4.70e-005
Zr-93	7.19e-008	2.68e-008	1.09e-006
Tc-99	1.33e-006	4.97e-007	2.02e-005
Pd-107	3.55e-008	1.33e-008	5.38e-007
Sn-126	5.33e-009	1.99e-009	8.06e-008
I-129	2.75e-007	1.03e-007	4.17e-006
Ba-133	4.53e-008	1.69e-008	6.85e-007
Cs-135	5.33e-008	1.99e-008	8.06e-007
Cs-137	5.33e-008	1.99e-008	8.06e-007
Sm-151	3.55e-009	1.33e-009	5.38e-008
Eu-152	3.55e-009	1.33e-009	5.38e-008

Table E.2. (Continued.)

Radionuclide	K_{r1}, yr^{-1} (waste to shallow soils)	K_{r2}, yr^{-1} (waste to subsurface soils)	K_{r3} yr^{-1} (subsurface soils to shallow soils)
Th-229	7.54e-011	2.82e-011	1.14e-009
Th-230	7.54e-011	2.82e-011	1.14e-009
Pa-231	2.22e-010	8.28e-011	3.36e-009
Th-232	7.54e-011	2.82e-011	1.14e-009
U-232	3.55e-009	1.33e-009	5.38e-008
U-233	3.55e-009	1.33e-009	5.38e-008
U-234	3.55e-009	1.33e-009	5.38e-008
U-235	3.55e-009	1.33e-009	5.38e-008
U-236	3.55e-009	1.33e-009	5.38e-008
Np-237	1.69e-006	6.29e-007	2.55e-005
Pu-238	1.78e-009	6.63e-010	2.69e-008
U-238	3.55e-009	1.33e-009	5.38e-008
Pu-239	1.78e-009	6.63e-010	2.69e-008
Pu-240	1.78e-009	6.63e-010	2.69e-008
Am-241	3.55e-008	1.33e-008	5.38e-007
Pu-241	1.78e-009	6.63e-010	2.69e-008
Pu-242	1.78e-009	6.63e-010	2.69e-008
Am-243	3.55e-008	1.33e-008	5.38e-007
Cm-243	1.33e-011	4.97e-012	12.02e-010
Cm-244	1.33e-011	4.97e-012	2.02e-010
Pu-244	1.78e-009	6.63e-010	2.69e-008
Cm-248	1.33e-011	4.97e-012	2.02e-010

Table E.3. Radionuclide half-lives and dose conversion factors.

Radionuclide[a]	Half-life (years)	DCF_{ing} (rem μCi^{-1})[b]	DCF_{inh} (rem μCi^{-1})[b]	DCF_{ext} (mrem yr^{-1} per μCi m^{-3} soil)[c]
Ac-227	2.18e+001	1.50e+001	6.70e+003	1.10e+000
Th-227				
Ra-223				
Rn-219				
Po-215				
Pb-211				
Bi-211				
Tl-207				
Po-211				
Am-241	4.32e+002	4.50e+000	5.20e+002	2.70e-002
Am-243	7.38e+003	4.50e+000	5.20e+002	5.60e-001
Np-239				
Ba-133	1.05e+001	3.20e-003	6.90e-003	1.20e+000
Bi-207	3.34e+001	4.90e-003	1.40e-002	5.90e+000
C-14	5.73e+003	2.10e-003	2.40e-005	8.40e-006
Cl-36	3.01e+005	3.00e-003	2.00e-002	1.50e-003
Cm-243	2.85e+001	2.90e+000	3.50e+002	3.60e-001
Cm-244	1.81e+001	2.30e+000	2.70e+002	9.80e-005
Cm-248	3.39e+005	1.60e+001	1.90e+003	5.50e-005
Co-60	5.27e+000	2.60e-002	1.50e-001	1.00e+001
Cs-135	2.30e+006	7.10e-003	4.50e-003	2.40e-005
Cs-137	3.02e+001	5.00e-002	3.20e-002	2.30e+000
Ba-137m				
Eu-152	1.36e+001	6.00e-003	2.20e-001	4.40e+000
Eu-154	8.80e+000	9.10e-003	2.60e-001	4.80e+000
H-3	1.23e+001	6.30e-005	9.50e-005[d]	0.00e+000
I-129	1.57e+007	2.80e-001	1.80e-001	8.10e-003
Kr-85	1.07e+001	0.00e+000	0.00e+000	1.40e+001[e]
Ni-59	7.50e+004	2.00e-004	1.30e-003	0.00e+000
Ni-63	1.00e+002	5.40e-004	3.00e-003	0.00e+000
Np-237	2.14e+006	3.90e+000	4.90e+002	6.90e-001
Pa-233				
Pa-231	3.28e+004	1.10e+001	1.30e+003	1.20e-001
Pb-210	2.23e+001	6.70e+000	2.10e+001	3.80e-003
Bi-210				
Po-210				
Pd-107	6.50e+006	1.40e-004	1.30e-002	0.00e+000
Pu-238	8.78e+001	3.80e+000	4.60e+002	9.50e-005
Pu-239	2.41e+004	4.30e+000	5.10e+002	1.80e-004
Pu-240	6.57e+003	4.30e+000	5.10e+002	9.20e-005
Pu-241	1.44e+001	8.60e-002	1.00e+001	3.70e-006
Pu-242	3.76e+005	4.10e+000	4.80e+002	8.00e-005
Pu-244	8.26e+007	4.00e+000	4.80e+002	1.30e+000
U-240				
Np-240m				
Ra-226	1.60e+003	1.10e+000	7.90e+000	7.00e+000
Rn-222				
Po-218				
Pb-214				
Bi-214				

Table E.3. (Continued.)

Radionuclide[a]		Half-life (years)	DCF_{ing} (rem μCi^{-1})[b]	DCF_{inh} (rem μCi^{-1})[b]	DCF_{ext} (mrem yr^{-1} per $\mu Ci\ m^{-3}$ soil)[c]
	Po-214				
Ra-228		5.75e+000	1.20e+000	4.20e+000	3.70e+000
	Ac-228				
Sm-151		9.00e+001	3.40e-004	2.90e-002	6.20e-007
Sn-126		1.00e+005	2.70e-002	9.60e-002	1.70e+001
	Sb-126m				
	Sb-126				
Sr-90		2.86e+001	1.30e-001	1.30e+000	1.50e-002
	Y-90				
Tc-99		2.13e+005	1.30e-003	7.50e-003	7.80e-005
Th-228		1.91e+000	3.80e−001	3.10e+002	1.56e+001
	Ra-224				
	Po-216				
	Pb-212				
	Bi-212				
	Po-212				
Th-229		7.34e+003	3.90e+000	2.00e+003	8.90e+000
	Ra-225				
	Ac-225				
	Fr-221				
	At-217				
	Bi-213				
	Tl-209				
	Po-213				
	Pb-209				
Th-230		7.70e+004	5.30e-001	3.20e+002	7.60e-004
Th-232		1.40e+010	2.80e+000	1.60e+003	3.30e-004
U-232		7.20e+001	1.30e+000	6.70e+002	4.60e-004
U-233		1.59e+005	2.70e-001	1.30e+002	8.70e-004
U-234		2.44e+005	2.60e-001	1.30e+002	2.50e-004
U-235		7.04e+008	2.50e-001	1.20e+002	4.70e-001
	Th-231				
U-236		2.34e+007	2.50e-001	1.20e+002	1.30e-004
U-238		4.47e+009	2.30e-001	1.20e+002	7.10e-002
	Th-234				
	Pa-234m				
Zr-93		1.53e+006	2.20e-003	3.50e-001	6.50e-005
	Nb-93m				

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[a] Radioactive daughters listed are those assumed to be in equilibrium with parents in the environment, and are not tracked separately in the calculations. Dose factors include contributions from these daughters.

[b] From DOE, 1988b.

[c] From Eckerman and Ryman, 1993.

[d] Corrected by a factor of 1.5 to include dose from dermal absorption.

[e] External dose factor for Kr-85 is the air submersion dose factor, in mrem y^{-1} per $\mu Ci\ m^{-3}$ in air.

Table E.4. Maximum activity and activity concentration in the surface soil compartment for the base case release scenario.

Radionuclide	Maximum Concentration (Ci m^{-3})	Maximum Activity (Ci)	Activity at 10,000 yr (Ci)
Ac-227	2.1e-007	1.6e-002	2.0e-003
Am-241	4.0e-009	3.0e-004	1.0e-009
Am-243	2.1e-012	1.6e-007	a
Ba-133	8.4e-016	6.3e-011	a
Bi-207	1.3e-019	9.6e-015	a
C-14	2.5e-007	1.9e-002	1.9e-002
Cl-36	2.7e-013	2.0e-008	2.1e-008
Cm-243	1.3e-014	9.5e-010	a
Cm-244	4.4e-012	3.3e-007	a
Cm-248	4.4e-018	3.3e-013	2.3e-013
Co-60	1.1e-012	8.3e-008	a
Cs-135	6.0e-013	4.5e-008	2.4e-008
Cs-137	8.3e-011	6.2e-006	a
Eu-152	3.6e-019	2.7e-014	a
Eu-154	2.7e-014	2.0e-009	a
H-3	4.8e-005	3.6e+000	a,b
H-3	2.3e-006	1.8e-001	a,c
I-129	1.0e-013	7.5e-009	3.5e-009
Ni-59	1.9e-013	1.4e-008	1.1e-008
Ni-63	2.1e-010	1.5e-005	a
Np-237	1.5e-009	1.2e-004	6.4e-005
Pa-231	2.1e-007	1.6e-002	2.0e-003
Pb-210	5.5e-006	4.1e-001	1.3e-002
Pd-107	1.2e-013	9.0e-009	4.7e-009
Pu-238	4.4e-009	3.3e-004	a
Pu-239	4.4e-007	3.3e-002	3.1e-002

Table E.4. (Continued.)

Radionuclide	Maximum Concentration (Ci m^{-3})	Maximum Activity (Ci)	Activity at 10,000 yr (Ci)
Pu-240	4.4e-008	3.3e-003	3.0e-003
Pu-241	7.1e-010	5.3e-005	a
Pu-242	1.6e-011	1.2e-006	8.0e-017
Pu-244	1.5e-020	1.1e-015	2.1e-017
Ra-226	5.5e-006	4.1e-001	1.3e-002
Ra-228	1.4e-008	1.0e-003	6.6e-004
Sm-151	5.0e-013	3.8e-008	a
Sn-126	7.6e-014	5.7e-009	4.3e-009
Sr-90	1.3e-009	9.8e-005	a
Tc-99	3.9e-011	2.9e-006	2.0e-006
Th-228	1.4e-008	1.0e-003	6.6e-004
Th-229	6.3e-011	4.7e-006	5.6e-007
Th-230	5.5e-006	4.1e-001	1.7e-002
Th-232	1.4e-008	1.0e-003	6.6e-004
U-232	3.0e-012	2.2e-007	a
U-233	9.2e-011	6.9e-006	1.6e-006
U-234	6.3e-006	4.7e-001	2.0e-001
U-235	2.2e-007	1.7e-002	1.1e-002
U-236	6.4e-009	4.8e-004	3.0e-004
U-238	7.6e-006	5.7e-001	3.6e-001
Zr-93	4.8e-013	3.6e-008	2.0e-008

[a] Peak occurs before 10,000 years; therefore, 10,000-year value is not used in dose calculations.

[b] Values shown are for the H-3 peak during institutional control at 17 years; used to calculate maximum offsite inhalation, external, and crop ingestion doses.

[c] Values shown are the H-3 values at 100 years; used to calculate maximum offsite milk and beef ingestion doses (cattle are not assumed to be grazed onsite before 100 years).

Table E.5. Calculated offsite air concentrations for non-volatile radionuclides at 10,000 years and at the maximum.

Radionuclide	Time of Maximum	Max. Air Conc. ($Ci\ m^{-3}$)		10,000 yr Air Conc. ($Ci\ m^{-3}$)	
		Cane Springs	Indian Springs	Cane Springs	Indian Springs
C-14	6498	3.7e-21	2.9e-20	3.3e-21	2.6e-20
H-3	17	6.5e-19	na[a]	0.0	0.0
H-3[b]	100	3.2e-20	2.5e-19	0.0	0.0
U-238	61,000	1.0e-20	2.2e-19	6.5e-21	1.4e-19
U-234	665,000	8.5e-21	1.8e-19	3.5e-21	7.4e-20
Th-230	711,000	7.4e-21	1.6e-19	3.0e-22	6.3e-21
Ra-226	713,000	7.4e-21	1.6e-19	2.3e-22	4.9e-21
Pb-210	713,000	7.4e-21	1.6e-19	2.3e-22	4.9e-21
Pu-240	7,000	5.9e-23	1.2e-21	5.4e-23	1.1e-21
Th-232	56,000	1.8e-23	3.9e-22	1.2e-23	2.5e-22
Ra-228	56,000	1.8e-23	3.9e-22	1.2e-23	2.5e-22
Th-228	56,000	1.8e-23	3.9e-22	1.2e-23	2.5e-22
Am-241	1,000	5.5e-24	1.2e-22	1.8e-29	3.9e-28
Pu-239	15,000	6.0e-22	1.3e-20	5.6e-22	1.2e-20
U-235	60,000	3.0e-22	6.4e-21	1.9e-22	4.1e-21
Pa-231	199,000	2.8e-22	5.9e-21	3.7e-23	7.7e-22
Ac-227	199,000	2.8e-22	5.9e-21	3.6e-23	7.7e-22

Table E.6. Maximum doses for transient occupancy scenario.

Radionuclide	Time of Maximum	Inhalation CEDE (mrem yr^{-1})	External EDE (mrem yr^{-1})	TEDE (mrem yr^{-1})
Ra-226	713,000	5.2e-03	8.8	8.8
Ac-227	199,000	1.7e-01	5.2e-02	2.2e-01
Th-228	56,000	5.1e-04	4.8e-02	4.9e-02
Th-230	711,000	2.1e-01	9.5e-04	2.1e-01
Pa-231	199,000	3.2e-02	5.7e-03	3.8e-02
U-234	665,000	9.8e-02	3.6e-04	9.9e-02
U-235	60,000	3.2e-03	2.4e-02	2.7e-02
U-238	61,000	1.1e-01	1.2e-01	2.3e-01
Pu-239	15,000	2.7e-02	1.8e-05	2.7e-02
Sum				**9.7**

Table E.7. Doses for transient occupancy scenario at 10,000 years.

Radionuclide	Inhalation CEDE (mrem yr^{-1})	External EDE (mrem yr^{-1})	TEDE (mrem yr^{-1})
Ra-226	1.6e-04	2.7e-01	2.7e-01
Ac-227	2.2e-02	6.8e-03	2.8e-02
Th-228	3.3e-04	3.1e-02	3.1e-02
Th-230	8.5e-03	3.8e-05	8.5e-03
Pa-231	4.2e-03	7.4e-04	5.0e-03
U-234	4.1e-02	1.4e-04	4.1e-02
U-235	2.1e-03	1.5e-02	1.8e-02
U-238	7.0e-02	7.8e-02	1.5e-01
Pu-239	2.5e-02	1.7e-05	2.5e-02
Sum			**5.8e-01**

Table E.8. Maximum doses for non-volatile radionuclides in the open rangeland scenario.

Radionuclide	Time of maximum	Inhalation CEDE (mrem yr^{-1})		Crop Ingestion CEDE (mrem yr^{-1})		Milk Ingestion CEDE (mrem yr^{-1})	Beef ingestion CEDE (mrem yr^{-1})	External EDE (mrem yr^{-1})	
		Indian Springs	Cane Springs	Indian Springs	Cane Springs			Indian Springs	Cane Springs
H-3[a]	100	1.7e-11	1.3e-10	1.7e-07	9.4e-07	7.9e-03	1.3e-03	0.0	0.0
C-14	6,830	7.5e-13	5.8e-12	5.4e-07	4.2e-06	4.3e-02	1.5e-02	2.0e-11	1.5e-10
Pb-210	713,000	1.3e-06	2.8e-05	1.1e-05	2.4e-04	7.3e-01	1.2e-01	1.8e-08	3.8e-07
Ra-226	713,000	4.9e-07	1.0e-05	1.1e-06	2.3e-05	1.9e-01	1.5e-02	3.3e-05	6.9e-04
Ac-227	199,000	1.6e-05	3.3e-04	4.9e-07	1.0e-05	4.3e-03	7.4e-04	1.9e-07	4.1e-06
Ra-228	56,000	6.5e-10	1.4e-08	2.9e-09	6.1e-08	5.2e-04	3.9e-05	4.3e-08	9.0e-07
Th-228	56,000	4.8e-08	1.0e-06	7.9e-10	1.7e-08	1.8e-06	2.9e-07	1.8e-07	3.8e-06
Th-230	711,000	2.0e-05	4.2e-04	4.4e-07	9.3e-06	1.0e-03	1.6e-04	3.5e-09	7.5e-08
Pa-231	199,000	3.1e-06	6.5e-05	3.6e-07	7.5e-06	7.9e-04	2.2e-04	2.1e-08	4.5e-07
Th-232	56,000	2.5e-07	5.2e-06	5.8e-09	1.2e-07	1.3e-05	2.2e-06	3.8e-12	8.1e-11
U-234	665,000	9.3e-06	2.0e-04	3.6e-07	7.6e-06	7.2e-02	3.3e-03	1.3e-09	2.8e-08
U-235	665,000	3.1e-07	6.5e-06	1.2e-08	2.6e-07	2.5e-03	1.1e-04	9.0e-08	1.9e-06
Np-237	53,000	8.6e-09	1.8e-07	2.0e-07	4.1e-06	6.5e-05	9.8e-05	9.1e-10	1.9e-08
U-238	61,000	1.0e-05	2.2e-04	3.8e-07	8.0e-06	7.7e-02	3.5e-03	4.6e-07	9.6e-06
Pu-239	15,000	2.6e-06	5.4e-05	3.5e-07	7.4e-06	1.4e-05	9.2e-06	6.8e-11	1.4e-09
Pu-240	7,000	2.5e-07	5.4e-06	3.5e-08	7.4e-07	1.3e-06	9.2e-07	3.4e-12	7.2e-11
Am-241	1,000	2.4e-08	5.0e-07	1.5e-08	3.2e-07	8.2e-07	9.8e-05	9.3e-11	2.0e-09
Sum:		**6.4e-05**	**1.3e-03**	**1.6e-05**	**3.2e-04**	**1.1**	**1.6e-01**	**3.4e-05**	**7.1e-04**

a While maximum offsite air concentration occurs at 17 years, maximum dose occurs at 100 years, which corresponds to the earliest time that cattle are assumed to graze onsite. The dose from ingestion of beef and milk dominates the dose for H-3.

Table E.9. Doses at 10,000 years for non-volatile radionuclides in the open rangeland scenario.

Radionuclide	Inhalation CEDE (mrem yr^{-1})		Crop Ingestion CEDE (mrem yr^{-1})		Milk Ingestion CEDE	Beef ingestion CEDE	External EDE (mrem yr^{-1})	